

Daylight and glazing specification: The impact on non-visual processes

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Summary

The aim of this thesis was to establish whether the choice of glazing system could be impacting on the well-being of building occupants beyond the response of the visual system, based on the daylight they receive within a building interior. Daylight utilization is inherent to the success of a building, and a number of parameters within the design of interior spaces have an impact on daylight distribution such as size of window and depth of room, as well as colour and reflectivity of surfaces. This thesis therefore also aimed to establish the relative importance of the choice of glazing in respect to these other parameters.

Through an extensive literature review of biomedical, neuroscience and chrono-biological research, a set of lighting parameters for the stimulation of non-visual responses were defined based on two processes; circadian entrainment (or phase-resetting) and subjective alertness. Whilst this biomedical research is inconclusive at the time of completing this thesis, these parameters provided a basis from which to assess the potential effects of different lighting environments with respect to the well-being of building occupants.

Physical measurements and a digital model of a Case Study room were used to establish the impact of a range of glazing systems on the light that reaches a person's eye. These studies showed that it is insufficient to rely on traditional horizontal illuminance measurements alone to ascertain whether a given space will provide enough light to support the non-visual system. It also showed that the effect of the glazing is strongly interconnected with other design parameters of the room, such as the colour of the surfaces. Overall though, the glazing specification had the most significant impact on the light that reaches a person's eye within the Case Study room.

In conclusion this thesis shows that, based on current understanding of non-visual lighting requirements, the choice of glazing does have an important impact on the non-visual processes connected to the eye. Of the variables within the control of the designer the specification of glazing has been shown to have the most significant impact. Further design guidance is needed to avoid the potential health implications of poor glazing choice.

DECLARATION

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

Signed  (candidate) Date 30.06.2015


STATEMENT 1

This thesis is being submitted in partial fulfillment of the requirements for the degree of PhD

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STATEMENT 2

This thesis is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by explicit references. The views expressed are my own.

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STATEMENT 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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Nomenclature

DF	Daylight Factor, a ratio of internal daylight illuminance to external daylight illuminance (expressed as a percentage)
E_i	is the daylight illuminance at an internal point on a working plane (lux = lumens/m ²)
E_o	is the simultaneous daylight illuminance on a horizontal external plane from an unobstructed hemisphere of overcast sky (lux = lumens/m ²)
θ	is the angle subtended by the visible sky measured in a vertical plane normal to the glass from the geometric centre of the window (degrees)
T	is the radiant flux transmitted by a material divided by that received (expressed as a number between 0 and 1)
A_w	is the net glazed area of the window less any lost to glazing bars or window frame (m ²)
ρ	is the overall mean surface reflectance value
A_r	is the total area of internal surfaces (m ²)
BER	is calculated Building CO ₂ Emission Rate (kg/m ²)
TER	is Target CO ₂ Emission Rate (kg/m ²)
A_p	is pupil size (mm ²)
E	is illuminance striking the surface being viewed (lux = lumens/m ²)
ρ	is directional reflectance of the surface toward the eye
K_m	is 683/lm (max. sensitivity for photopic vision which occurs at 555nm)
V_λ	is the value of the photopic spectral luminous efficiency function for that wavelength
I	is intensity of light that passes through a material (cd = lumen/steradian)
I_o	is initial intensity of light (cd = lumen/steradian)
ϵ	is molar absorptivity (L mol ⁻¹ cm ⁻¹)
b	is path length of the sample (cm)
c	is concentration of compound in material (mol L ⁻¹)
R	is radiant flux reflected by the surface of a material, divided by that received (expressed as a number between 0 and 1)
A	is radiant flux absorbed by a material, divided by that received (expressed as a number between 0 and 1)
T_v	is spectral flux, within the visible spectrum, transmitted by a material, divided by that received (expressed as a number between 0 and 1)
R_v	is spectral flux, within the visible spectrum, reflected by a material, divided by that received (expressed as a number between 0 and 1)
U-value	is a measure of heat loss from a specific building component such as wall or floor (W/m ² K)
SHGC	is Solar Heat Gain Coefficient (expressed as a number between 0 and 1)
LSG	is Light to Solar Gain ratio (expressed as a number between 0 and 1)

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Chapter 1

The role of light in Architecture

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1 Introduction

1.1 Aim

The aim of this thesis is to establish whether the specification of glazing systems within modern buildings has a significant impact on the health and well-being of the building occupant. Building users typically have an innate response to daylit spaces with '*light and airy*' being a common reply to a question of preference for internal environments. Whilst the sensitivities of the human visual system are well established, the impact of light stimuli on the human body beyond the visual system, described in this thesis as the non-visual responses to light, are less well known.

This thesis will establish whether the quality and quantity of light is important for supporting physiological well-being of the building occupant beyond the visual system. An objective of the thesis will be to examine the connection between the light that people receive at the eye and physiological processes which are separate to vision. This will establish whether the source of light is more significant for sustaining well-being than currently thought, focusing on the role of daylight within building design.

There are a number of parameters which affect the amount of daylight that reaches a building occupant, one of the most significant being the choice of glazing system. As the threshold between outside and inside, the glazing system within a building envelope filters any daylight that reaches the building interior. The design and specification of glass and glazing systems is influenced by a number of factors such as thermal performance and aesthetic appearance of the building facade. The impact on occupant well-being is not currently a factor that is considered by glazing manufacturers and designers. Another objective of this thesis will be to ascertain whether the design and specification of glazing systems ultimately has a more significant impact on well-being of the building occupant.

As mentioned above the specification of glazing is one of a number of parameters within the design of interior spaces that have an impact on daylight distribution such as number and position of window within wall, area and depth of room, as well as the specification of the internal finishes. This thesis also aims to establish the relative importance of the specification of glazing in reference to these other parameters. As this thesis takes an interdisciplinary approach the following section sets out a roadmap to the thesis describing what will be covered in each chapter.

1.2 Roadmap to the thesis

In this thesis the aim will be explored in the following chapters. Chapter 1 examines the significant role of light as a design tool within architecture, whether that is functional, theoretical, or phenomenological. Chapter 2 will establish how the human visual system responds to light and current guidance for designing with daylight before the methodology for the thesis is outlined in Chapter 3.

Chapter 4 will provide an extensive literature review of biomedical research and the role of the light within the human body beyond the visual system and the implications for daylight design. Chapter 5 will establish the availability of daylight as a light source for the built environment and methods for accurately assessing this based on geographical location. Chapter 6 will assess the role of the glazing system and how it affects the light received within buildings. Chapter 7 will bring these two previous chapters together with an initial evaluation of the specification of glazing and its effect on the light that reaches the internal face of the glazing system, the initial threshold of the building interior.

Chapter 8 & 9 will look in more detail at the light that reaches the building occupant based on the design parameters of a Case Study room and more specifically the relative impact of the choice of glazing system. Finally Chapter 10 will bring the findings of the thesis together in the conclusions. This roadmap is graphically represented within Figure 1.1.

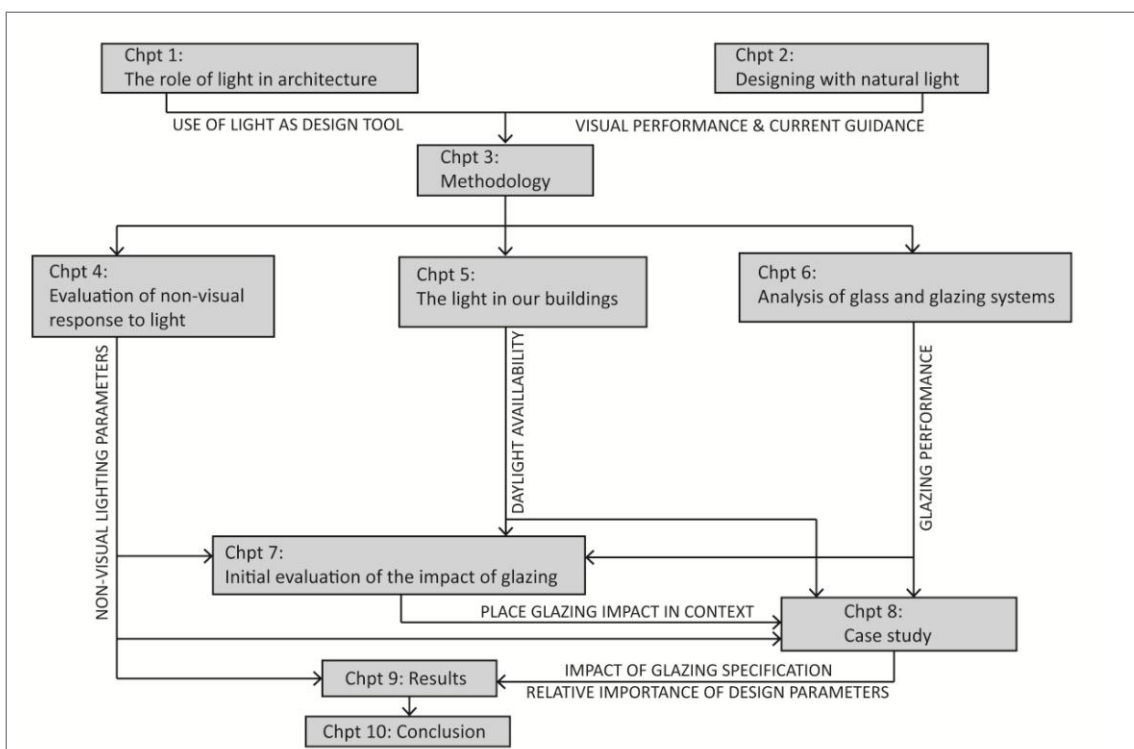


Figure 1.1: Flowchart describing thesis structure

1.3 The role of light in Architecture

This Chapter will provide the background to the thesis, describing the inherent role of light in shaping how people perceive the world around them. It will establish the value of natural light within architectural design as well as the significance of the connection with human physiological well-being of over and above visual performance.

Light gives all objects life, animating them with form and shadow; without it people would not perceive the world around them. A space is only realised by the light that falls on the surfaces within it, everything from the details to the overall volume are all created by the interaction with light. The dynamic variability of daylight is something that both artists and architects often explore within their artwork or buildings to influence the experience and reaction of the observer (Rasmussen, 1959). As Norman Foster expresses in the foreword to David Loe's guide to Daylighting Design (Loe, 1998) the history of architecture is rich in the diversity of its response to light. This instantaneous quality of daylight is perceived by the eye, one of the human body's most powerful sensory organs and this information is transmitted to the brain.

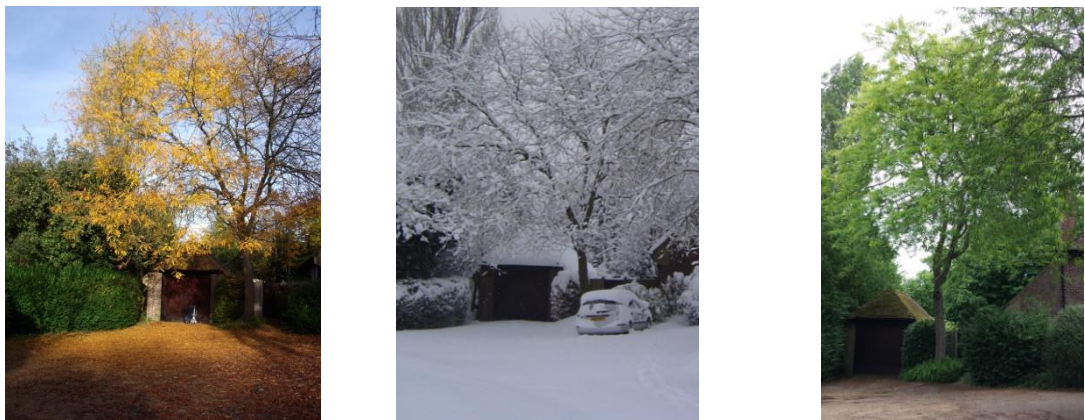


Figure 1.2: The changing seasons clearly depicted in the changing colour and light within this natural scene (author's own)

Light is a fundamental tool in the creation of functional as well as inspiring spaces. Light can be provided from both natural and artificial sources which often result in very different characteristics. Thomas Edison's pioneering invention of the light bulb in 1879 provided the means to artificially create light, to illuminate any space at any time of day or night, changing the internal environment of buildings and more significantly the way people lived their lives. The mass production of a wide array of lamps and the availability of cheap fuel after the Second World War brought with it the realisation that light could be simulated artificially with a greater ease and flexibility than afforded by natural means. The reliance on daylight as a

source of light therefore receded along with it some of the inspirational aspects of daylight buildings.

1.3.1 Vision as one of five senses

People interpret and navigate the space around them from information collected through their senses. There are five main senses that provide information to the brain; auditory, olfactory, touch, taste and vision. Vision is often considered to be the primary sense with approximately 80% of the information from the surrounding context provided by vision whether this is done consciously or subconsciously (Pease & Pease, 2004). Vision is often used to confirm the information that is received by the other senses such as hearing. The eye is a complex organ which adapts to different lighting scenarios to maintain a level of information about the surrounding context which is in turn passed to the rest of the body. This information is supported by the other senses but it is vision that is dominant.



Figure 1.3: Image from *Chromosaturations* (2013) exhibit by Carlos Cruz-Diez taken from exhibition publication (Luckett & Manchester, 2013)

Light is more accurately described as the part of the electromagnetic spectrum to which the photoreceptors within the eye are sensitive. The eye collects and transmits information to the brain as electrical signals from the surrounding context, and depending on the light that is received, different receptors within the eye respond. This range of different photoreceptors allows the visual system to adapt to a wide range of lighting scenarios. Human perception and the reaction of the eye to light stimulus is often exploited by light

artists whether this is using natural or artificial light. For example, in a piece recently exhibited at the Light Show exhibition at the Haywards Gallery, London

(2013) seen in Figure 1.3, Carlos Cruz-Diez's interactive artwork *Chromosaturations* (2013) manipulates the observer's response to the space using the fact that the human retina is accustomed to receiving a wide range of wavelengths or colours of light at the same time.

By providing three rooms with monochromatic light; red, blue and green it stimulates the varying spectral sensitivities of the three cone cells within the human retina (Luckett & Manchester, 2013). This results in the viewer having a disorientating journey through the rooms as their eyes adapt to the different lighting scenes. The transition between them allows the viewer to experience the adaptation of their own vision, not something that people are familiar with experiencing. These manipulations of light and human perception underline the inherent physiological connection with the optic sense and the fascinating connection between the eye and the brain. This physiological response also has a psychological effect on some observers.

1.3.2 Perception of time and space

There is great beauty in the variation of light depending on the time of day and the season. An awareness of the changing quality of daylight connects both animals and humans with their surroundings. This changing quality of natural light is captured in the work of many artists such as Vermeer, 1632-1675, a Dutch Baroque painter renowned for his masterly use of light. He often used the play of light on his subjects to create dramatic, narrative scenes within his paintings (Rasmussen, 1959).

A more recent piece by artist Susan Chorpenning called '*Light Rooms*' records the memory of sunlight coming in through the windows on the walls and floors of a room. In one of the installations Chorpenning depicts a fabricated memory of light falling onto the floor and it was said to still have a profound effect on the viewer who felt an increased sense of brightness within the room.

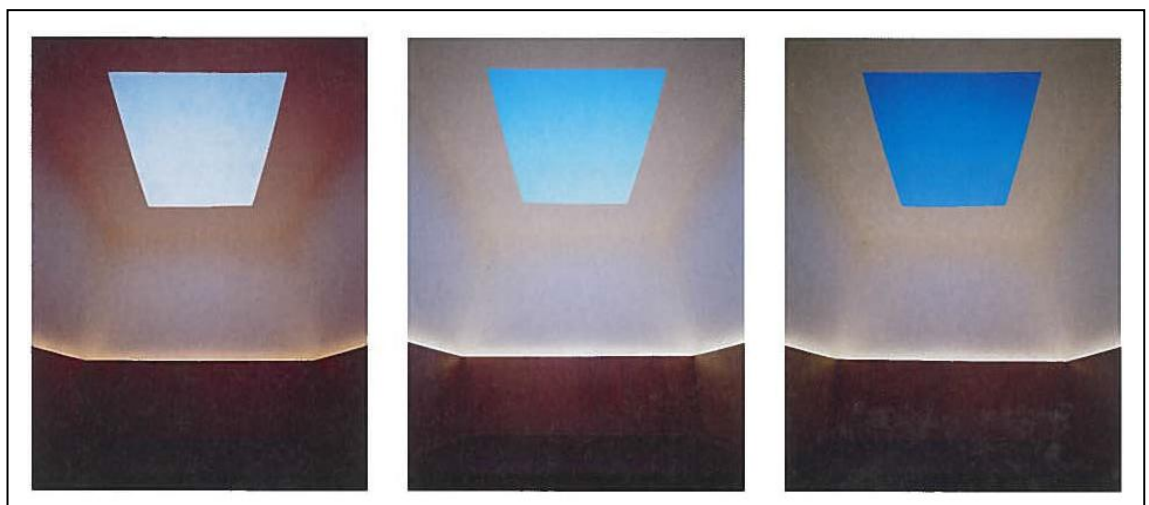


Figure 1.4: A sequence of images from *Light Box* by James Turrell taken from Luckett & Manchester (2013)

Drawing the viewer's attention to the presence of natural light is also the focus of James Turrell. Turrell's art pieces, particularly *Light Box* shown in Figure 1.4, fall between art and architecture as one-to-one installations that place the viewer at the centre of the piece with a defined focus. Turrell uses the strength of natural light to draw the attention of the viewer in an attempt to manipulate their reaction, wanting the viewer to focus on the changing quality or colour of natural light. These artists are all driven to explore the changing nature of daylight and its effect on the viewer, exploring the phenomenological impact of space enhanced by daylight which continuously surrounds us.

The highlights that the effect of the shape and position of windows within the building envelope on the resulting perception of light is often at the heart of the design concept. This was one of the main drivers for John Soane. Throughout his work Soane was concerned with the power of light and how it could transform a space. As acknowledged by Dixon & Muthesius (1978) Soane used the term *mysterious light* derived from Le Camus de Mézières. It was something that he spent his life trying to capture. It is often suggested that he used his house at Lincoln's Inn Fields, London developed 1792-1824 as a testing model for his larger building schemes.

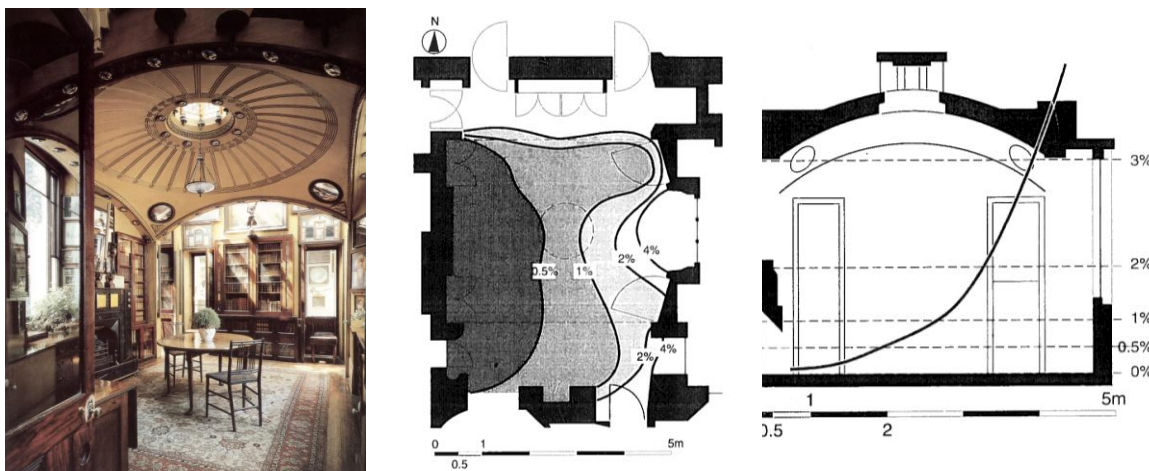


Figure 1.5: Images from the interior of the breakfast room at Lincoln's Inn Fields by Sir John Soane as well as plan and section showing daylight factor distribution taken from Fontoynt (1999).

The building consisted of a house and a museum in which Soane experimented with numerous different shapes, sizes and locations of windows to explore the impact it would have on the daylight within the space. Fontoynt (1999) presents an interesting evaluation of these different daylit spaces, clearly showing the different distribution of daylight achieved as shown in Figure 1.5 above. One space in particular was the Breakfast Room, the domed roof

structure and high level windows throw a mysterious diffused light throughout the space. In other parts of the house in Lincoln's Inn Fields Soane also experimented with changes in level, top-lighting to model different daylighting techniques as well as using mirrors. In line with developments in construction techniques, architects have been afforded the ability to play with the position and size of windows in building facades.

1.3.3 Psychological impact of light

Delivering a good daylit environment is more than just task lighting; lighting in general should be about more than just creating good lighting for the performance of visual tasks. People's perception of a space is derived of more than whether they can see to read a book or make a cup of tea. As Peter Davey (2004) expresses in his article *Light and Dark*, the sensation people experience within a space is due in part to light. Light influences how the occupant perceives their space as well as having an impact on their psychological well-being.

A number of authors of lighting publications have acknowledged this, for example, William Lam (1992) pays greater attention to the effect that daylight can have on the occupant than the energy consumption or its modelling qualities. Lam suggests that the *conventional* methods for lighting design where the process starts with copying values from a handbook has its problems; this suggestion that *striving for quality is often driven by an attempt to avoid the unbearable rather than define what is pleasing* is still common today. The text goes on to say that lighting has an effect on human health with respect to the psychological effect of visual perception on comfort and productivity. Lam suggests that a design process motivated by lighting handbooks is inappropriate to successfully align the needs of the occupant with the lighting environment. He highlighted that a new system is needed where the main focus should be to create successful spaces driven by the perception of the occupant rather than a numerical exercise.

Moore (1985) began to explore the relationship between lighting and visual perception and the effect that this could have on the occupant. He suggested that many lighting engineers discourage people from using daylight as a source of illumination as the absolute amounts are unpredictable, unlike for artificial lighting. He acknowledges the fact that this may not result in the most successful spaces as the eye may not perceive light in the same way as a photometer. This highlights the important distinction between people's perception of a space based on overall brightness and view and the requirements for visual task performance. This publication by Moore emphasises the preference of some lighting designers for the control and flexibility

afforded by artificial light sources and the potential impact this has on the design and experience of interior spaces for the occupant.

This difference is particularly evident when it comes to the uniformity of light across a space. Lighting guidance such as the British Standards (British Standards Institute, 2008) (British Standards Institute, 2011) and Society of Light & Lighting's Code for Lighting (CIBSE, 2012) suggest that uniformity is important for successful lighting design however this may not provide the most suitable environment for the occupant. Over thirty years ago Benjamin Evans (1981) was acutely aware that although lighting standards recommend that the best conditions for visual performance might be within uniform environments, the effect on human perception of light shows that uniformity is not necessarily the most stimulating environment. This in turn could have a knock-on effect on productivity. He acknowledged that the continuously variable nature of daylight provides a valuable change of stimuli inherent to human physiology and that the proper introduction of daylight into a space is the simplest and most effective way of providing this variation.

Although lighting design has traditionally been associated with providing adequate illuminance levels for a given set of activities or tasks more recent research has identified the importance of visual interest or variety within an interior space. A number of researchers and authors of lighting guidance (Baker, Fanchiotti, & Steemers, 1993) (Loe & Tregenza, 1998) acknowledge this but it has not yet fully translated into an adjustment of lighting design of many spaces people inhabit.

The importance of the connection between an individual's light history and how they respond to a specific lighting environment is an area that is also under debate and may have a significant impact on how they respond to a space. As acknowledged by Loe & Tregenza (1998) some perceptual connections are possibly dependent on past experience, the changing colour and patterns of light trigger associations with places experienced in the past and give clues as to the nature of a room. As with other experiences that stimulate the senses, a residing memory may influence a person's response to the lighting environment within a specific interior space. This is often the case with the olfactory sense where memories of a particular time or place are recalled by a specific smell such as newly cut grass or freshly laundered clothes. It may also be the case that the brain retains light information for other physiological responses beyond the length of time it takes to process the visual information.

1.3.4 A view/connection with the outside

The window or more literally the opening in a building envelope which allows light to penetrate in the building interior has been an important component of architectural design long before the term 'high architecture' became common-place. When looking at vernacular architecture it is clear that the window was vital for multiple functions including environmental control, maintaining ventilation and light to the internal spaces as well as security, providing a view of external areas.

It is evident from early civilisation settlements, allowing light into a space was a vital function of the building envelope, even when there was no glass to protect the occupants from the harsh external environment. Allowing daylight into the space was a priority over protection against the elements which can clearly be seen in the architecture of Celtic farmhouses in Wales as shown in Figure 1.6.



Figure 1.6: Y Garreg Fawr: Early medieval farmhouse from Celtic civilisation, photograph taken at St Fagan's National History Museum (Authors own)

Through the history of architecture the significance of the window within the building envelope gradually increases. With the Renaissance came a new understanding of the use of the window and glass. Whilst Gothic architecture had been more about drama through illumination than transparency, in the 16th Century the growing European aristocracy wanted to exploit the qualities of glass to bring a view to their great houses. Hardwick Hall as seen in Figure 1.7, built in the 1590s by Robert Smythson, was a good example of this and has been described as 'more glass than wall'. This brought with it problems of thermal comfort and saw the occupants having to move around the house with the seasons in order to live in a comfortable environment as described by Wigginton (2005). It became apparent that with abundant daylight came potential problems as a result of direct light from the sun and the inadequacy of glass as a base material for solar control or thermal resistance.

The development of plate glass in 1676, following research by the French government, paved the way for the development of the conservatory. This was partly driven by European explorers who identified the need to protect the plants that they had been importing from around the world. By the 19th century conservatories had become great pieces of architecture with the use of glass as a material in construction spreading to much larger, public buildings, the greatest example being Crystal Palace built for the Great Exhibition in 1851.



Figure 1.7: Hardwick Hall, Derbyshire, Robert Smythson 1590-97 (National Trust)

1.3.5 Architectural aesthetic of glass

From functional buildings to those more driven by aesthetic transparency a building facade has as much a theoretical role as a functional one. Industrialisation and the development of better construction techniques had demystified the role of light in architecture but it still remained a key element in architectural design. In the early 20th century architects such as Walter Gropius and Mies van der Rohe were exploring the architectural possibilities of glass and its use was spreading from industrial buildings to public buildings. Michael Wiggington (2005) suggests that this obsession that started in the second decade of the 20th century had the most significant influence on architecture and in particular its relationship with glass. The suggestion that there was a link between the physical transparency and openness it provides within buildings could translate into a more of a social agenda was clear. The Farnsworth house, 1946 by Mies van der Rohe became symbolic of this architecture, where the walls were said to disappear into the surrounding landscape. This physical and theoretical transparency within architectural can be seen in many buildings today in particular modern government buildings such as the Senedd building in Cardiff, UK or the new Reichstag in Berlin, Germany.

One of the architects most prolific in his use of natural light, Louis Kahn, believed in the mystical nature of daylight which defined space, famously being quoted as saying that you could not create space without natural light. For Kahn making 'the room', which he saw as one

of the essential elements of architecture, was the manipulation of structure and light. This is a concept which he implemented in a number of his buildings, particularly in his later work. It was a theory that drove him throughout his career. A clear example of this is the Kimbell Art Museum shown in Figure 1.8 in which daylight is integral to each gallery space which the architect suggests gives it the essence of a room. The crown of the barrel vaulted roofs is split letting light in along the full 100 ft length, positioning the opening where the keystone should sit shows that the roof is not in fact structural.



Figure 1.8: Kimbell Art Museum, 1966-72, Louis Kahn taken from Brownlee & De Long (1997)

1.3.6 Status associated with daylight

Religious architecture embodied this fascination with light. Romanesque architecture can be simply translated as being developed from the concepts and precedents set by the Roman Empire and particularly the grand architecture of Rome. As outlined by Wigginton (2005) this influence of architecture from a warm climate gave Romanesque buildings deep walls, large vaults and small windows. This architecture created a powerful statement of both the presence of God as well as stabilising the temperature and the small windows controlled what could be a very strong light. These places could be dark and this style of architecture did not fulfil the desires of many who longed for bigger, dramatic spaces with greater illumination within which the masses could worship.

The manipulation of natural light began in Christian architecture in the early Middle Ages when people saw light as a 'symbol of their saviour', the psychological power of natural light and particularly sunlight being used to provide drama in churches. This was cemented by the arrival of Gothic architecture from France at the middle of 13th Century where natural light and sunlight in particular were used to create drama in new cathedrals and churches through the introduction of stained glass windows. As Watkin (2000) enthuses, the other worldliness

or divine atmosphere within these spaces was heightened by the richly coloured light from these windows. This technique could be used to depict the stories as shown in Figure 1.9.



Figure 1.9: Christian scene depicted within a stained glass window within the Tudor Chapel at the Vyne, Hampshire (author's own)

Benedictine Abbot Suger, an important patron of this new architecture, saw light as one of the fundamental elements of this new style that began in the construction of cathedrals. In his accounts of the church of St-Denis near Paris described in Moore (1985) Suger talks of *the wonderful and uninterrupted light of most luminous windows, pervading the interior beauty*. This can be clearly understood when visiting places such as Sainte Chapelle in Paris, built 1243-48, shown in Figure 1.10. Throughout the day the characteristics of the daylight streaming in through the vast area of stained glass continually changes the atmosphere of the space.



Figure 1.10: Interior of Saint Chappelle, Paris (author's own)

New understanding in construction techniques made way for new building geometries ending the reliance on the Romanesque barrel vault as well as new technologies such as new ways to cut, lift and bond stone, meant that larger volumes of spaces could be created. This also meant that the traditional heavy dividing walls could be replaced by slender columns making room for significantly larger and uninterrupted areas of glass. Colour and light could now be brought into the heart of the cathedral, the inherent quality of glass to transfer colour with more power and drama through the changing quality of daylight than painting.

By the end of the 19th Century, reinforced concrete had been developed and its use prolific in the US where Albert Kahn built a number of factory buildings using this technique, famously the Ford Motor Company. This construction technique meant that the façade of the building could be separated, to a certain degree, from the structural stability and could therefore incorporate large windows providing a naturally lit, well ventilated space for assembly line workers. This was followed not long after by the birth of the curtain-wall with the construction of the Hallidie building in San Francisco by Willis Jefferson Polk in 1918. This did however lead in some instances to an increased reliance on mechanical systems to provide heating or cooling for internal environments to support occupant comfort.

1.3.7 Artificial light

This move away from the value of daylight within internal spaces is supported by the fact that appropriate light levels can be achieved by artificial means. With the invention of the lightbulb in 1879 by Thomas Alva Edison any environment could be illuminated at any time of the day; this in particular provided the means for spaces to be lit after dark. However it also saw the use of daylight within buildings seriously deteriorate, due to the ease and seemingly flexible nature of artificial light. By the 1960s due to the availability of cheap fuel as well as reliable mechanical equipment, the prevalence of artificial light sources significantly increased.

The invention of the fluorescent light accelerated the development of the deep plan office in USA during the 1960s plunging the American population into artificially lit interiors. With the aid of new structural technologies office spaces reaching depths of up to 12 metres could be created, achieving what appeared to be acceptable internal lighting levels with artificial lighting. As acknowledged by Kraemer, Sieverts & Partner (1977) in the new deep, open plan offices it was only possible to provide good, sufficient visual and working conditions by using artificial light sources. With these relatively cheap new technologies becoming more readily available it is easy to understand how the seemingly 'easy-to-control' artificial light source took over from inherently uncontrollable daylight. By the 1990s the biggest selling light source was a 'cool white' fluorescent lamp. This was the cheapest on the market.

Nevertheless, people still enjoy and often prefer to inhabit daylit spaces and this has been shown by a number of studies into occupants' perception of the spaces they inhabit. A survey of a selection of office staff referenced in the Society of Light and Lighting, Daylighting and Window Guide LG10 (CIBSE, 1999) showed that 80% of people surveyed said they would prefer

to sit next to an (openable) window. When the majority of people spend most of their lives indoors in spaces lit with artificially simulated light daylight can sometimes be seen as a luxury, often treated like a status symbol associated with company hierarchy or prestige (Guzowski, 1999) (Veitch & Newsham, 1998).

Even though in an increasing proportion of new buildings the size of windows have been significantly reduced, the occupant still has a great deal of preference towards daylight spaces and to have an office desk near to the window (Heschong Mahone Group Inc, 2003b) (Aries, Veitch, & Newsham, 2010). In a world where productivity and company performance are becoming the driving forces behind industry and studies have shown that access to bright light, particularly daylight, improves productivity particularly during winter months (Rea, 2002a) (Aries, Veitch, & Newsham, 2010) providing a lighting environment where employees feel comfortable and at ease should be of greater importance.

1.3.8 The connection between energy efficiency and the lighting environment

The changing drivers of architectural design have more often than not been connected to the role of daylight until recently when sustainable development and the reduction of CO₂ emission and energy consumption have become key design drivers.

The drive towards zero carbon and improved energy performance of buildings placed the spotlight on the thermal efficiency of all building components. Although natural light and ventilation offer a potential free resource they have become an area of potential risk. Building regulations are continually tightened around building performance, forcing designers and contractors alike to find new ways to reduce energy consumption and relative CO₂ emissions of their new buildings. Therefore buildings are to an increasing degree sealed from their surrounding context, the internal environment closely controlled by mechanical systems.

This emphasis on closely controlled internal environments has to some degree taken with it the architect's freedom to design spaces based on the natural resources available to them and to fully embrace the experience of these elements within the building. Advances in technology and material science have allowed manufacturers and designers to improve the performance of buildings but this has sometimes been at the detriment to the experience of the building occupant.

It is only more recently that the desire to have greater areas of glass providing an abundance of natural light has been outweighed by a concern over the thermal properties of this material.

Where construction budgets are still high the proliferation of fully glazed facades to wrap high end office environments continues while at the other end of the spectrum there is a reduction of window openings to the bare minimum. Driven by a reduction in heat loss as well as heat gain and the relatively poor thermal performance of glass and glazing as a building component, glazing has often been reduced to the minimum acceptable size. This reduction goes some way to satisfying the stringent thermal performance requirements as an alternative to expensive multi-layered glazing systems. Large expanses of glass are a costly addition to a new development both from the point of view of the initial construction as well as a longer term building operations and maintenance.

Advancements in technology and materials science as well as software to accurately model the performance of these components have resulted in significant improvements in the performance of glazing. This development has mainly been focused on the thermal properties of glass and glazing systems with manufacturers spending a substantial amount of time and resources in the pursuit of efficient systems. The impact of these advanced glazing systems on daylight penetration to support the well-being of the building occupant has been considered of lesser significance. With the flexibility and efficiency afforded by artificial light sources adequate lighting environments can be maintained without the reliance on daylight. The inclusion of windows seems to be disconnected to the need to provide a good quality lighting environment that supports the well-being of the occupant.

1.3.9 Daylight and well-being

The connection between natural light and well-being has been woven through architecture for centuries. The highly civilised Roman and Greek society bestowed great emphasis on creating developed urban areas where occupant well-being was paramount with sophisticated sanitation systems as well as regulations for building standards which included natural light. This was part of the minimum lighting standards both the ancient Greeks and Romans commanded for their cities. As Moore (1985) describes, the British Law of Ancient Lights which dates back to 1189 and was later embodied into statute law as part of the Prescription Act of 1832 stated that if a window enjoyed uninterrupted access to daylight for a twenty year period then it became a permanent right.

The development of construction techniques and new materials meant that light could be brought into all building types. This played a central role within the architecture of the Victorian era, where window openings were given as much area as possible to maximise the

amount of daylight brought into internal spaces. The use of load-bearing lime concrete foundations to aid the use of cast iron beams was widely introduced into the construction of public and domestic buildings, pioneered by Sir Robert Smirke. This construction technique using cast iron had already been a feature of industrial architecture in the late 18th century and meant that the wall could become independent of the structure.

As Watkin (2000) notes that the introduction of cast iron into the construction of buildings in the late 18th Century made it easier to introduce large window openings into building façades. Sanitary improvements, in which daylight requirements were also acknowledged, became of great importance in this period of growing wealth with bye-laws specifying the minimum window size for each room within a house, so as to ensure adequate lighting (Dixon & Muthesius, 1978). New construction materials also brought about the development of more expansive shop fronts and the introduction of the shopping arcade, bringing greater amounts of daylight into building interiors. In the opinion of Sophia and Stefan Behling (2000), the Georgian house with its large windows and increased ceiling heights provided the right balance between bringing natural light into the plan and insulation to provide thermal comfort.



Figure 1.11: Image of a Nightingale ward at St Thomas' Hospital, London 1890 (Nightingale, 1982)

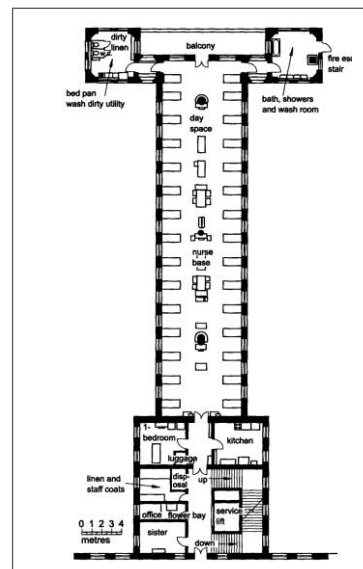


Figure 1.12: Plan of a Nightingale ward (Nightingale, 1982)

Medicine and the design of healthcare buildings have to a certain degree acknowledged the connection between natural light and well-being. Florence Nightingale highlighted the importance of exposure to natural light and ventilation in her *Notes on Nursing* (1974 (first

published 1859))¹. The Nightingale ward, still seen in many hospitals today, was designed around the requirement that every patient should be exposed to large quantities of natural light as well as access to a view out with each bed placed between two large windows as shown in Figure 1.11 and Figure 1.12. This connection between natural light and health continued with the discovery of the remedial effect of sunlight on the symptoms of Jaundice by a nurse looking after premature babies. It was furthered discovered that in fact blue light was the most effective at treating the condition with these findings first published nationally in 1958. Phototherapy is now commonly used to treat neonatal jaundice.

1.3.10 Potential consequences of the reduced importance of daylight

Advances in technology and material science have allowed manufacturers and designers to improve the performance of buildings but this has sometimes been at the detriment to the experience of the building occupant. An understanding of the technical requirements and rating a building in terms of its energy performance may not guarantee that space will support the well-being of the people that use it, whether that is psychologically or physiologically. As noted earlier this can result in designing buildings through a 'checkbox' process. This has not been seen anywhere quite as vividly as new housing developments such as in Figure 1.13.



Figure 1.13: Recently completed affordable housing development in Oxfordshire, UK (author's own)

Significant cost constraints as well as the focus of building regulations heading towards zero carbon has meant that building design has somewhat turned its back on the value of daylight. With the control and cost efficiency of artificial light sources internal lighting environments can be achieved without the need for daylight which in turn has often led to a

reduced percentage of glazing within the facades of buildings. These design drivers have left a large percentage of the affordable housing market in particular with significantly reduced window area but it has also affected schools and low to mid-range office environments.

¹ *It is the unqualified result of all my experience with the sick, that second only to their need of fresh air is their need of light; that, after a close room, what hurts them most is a dark room.* Quote from Notes on Nursing, Nightingale F.

The inclusion of windows can often seem to be connected more closely with the desire or need to provide a view rather than to provide a good quality lighting environment that supports the well-being of the occupant. This can be seen clearly with the site and building layouts on new building estates where the density of the development and a housing target are the key design driver. These houses often take no consideration of sun path or daylight availability with the arrangement based on a standard template.

In densely populated areas such as in some large cities the in UK some people do not have direct access to a garden or outdoor space. Research has shown that there are increased cases of Vitamin D deficiency in these densely populated areas (Davies & Shaw, 2011). In these circumstances the internal environments within which they live or work need to provide adequate light to support their well-being as well as visual performance.

1.4 Summary and conclusions of Chapter 1

The use of light has played a pivotal role in the development of Architecture from a theoretical as well as functional point of view. It has also played a significant part in the development of building design to support the well-being of the people that inhabit them. The connection between well-being and daylight has been understood since ancient Greek civilisations and this continued connection can be seen through the evolution of vernacular architecture. More recently the construction industry has been driven by other pressures such as the reduction of energy consumption and CO₂ levels which has in turn influenced the performance characteristics of key building components as well as the overall aesthetic.

The window or glazing system is often the worst performing component due to the poor thermal resistance qualities of glass as a material. This poor performance has often led to significantly reduced amounts of glazing particularly in the facades of buildings where energy reduction and therefore thermal performance is a key requirement. This reduction in window area often forces the inhabitants to rely on artificial sources to provide a satisfactory amount of light within the internal spaces. As well as within housing developments, this can also be the case within other building types such as schools, offices and hospitals where people spend a significant proportion of their daily lives.

The human body evolved under the changing qualities of light from the Sun, and it is plausible to consider that reducing people's exposure to daylight due to an increased amount of time spent indoors could have a harmful effect on their well-being. Although artificial lighting can satisfy requirements of visual performance, with many designers reliant on the control over quantity and spatial distribution it affords them, it may not provide the necessary lighting quality to support well-being with controlled intensity and static spectrum.

If the specific characteristics of light are important to maintaining well-being, the material properties of architectural glazing could have an increased importance. The glazing components are the threshold between the external and the internal environment through which light is transmitted and filtered. This thesis will establish how the specification of these window systems affects the daylight received within the internal environments people inhabit and in turn its affect on the light needed to maintain well-being.

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Chapter 2

Designing with natural light

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2 Designing with natural light

This chapter will provide an outline of how natural light is incorporated into building interiors, the guidance provided for architects and lighting designers as well as the standards to which they need to adhere for the provision of daylight within building interiors. In order to provide a lighting environment that is suitable for the activities that take place within a building as well as one that offers interest and enjoyment it is important to understand how the human visual system responds to light information.

Chapter 1 provided a picture as to the phenomenological role light plays within architecture and how people perceive light within space. This chapter will build on this and provide an outline of the physiological response to light, how the eye collects and transmits light information from its surroundings and how the design of buildings can have an impact on the lighting environment.

Acknowledging the process of evolution suggests that this inherent preference could be based in our physiology. Baker, Fanchiotti and Steemers (1993) acknowledge that the types of light that are received by the eye could turn out to be as vital to well-being as the kinds of food eaten suggesting that light that is significantly different to that which has been provided by sunlight may cause the equivalent of malnutrition.

2.1 Performance of the human visual system

Since biomedical investigation as well as philosophical research around the human visual system in the 17th Century (Descartes, 1637/2001), the eye as a receptor for light is one of the most thoroughly investigated organs within the human body. Until recently this research has focused on what was believed to be the sole function of the eye as the main organ of the visual system providing visual information to the brain in order that it could understand and respond to the surrounding context. This knowledge has informed the broad area of photometry, ranging from the technical requirements for artificial lamps as well as guidance on daylight design of buildings.

The eye is a complex organ. It responds to the variety of lighting environments we encounter in different ways depending on which parts of the retina are activated. There are a range of parameters within which the visual system performs relating to the intensity as well as the spectral quality of light. These parameters will be briefly described below in order to understand the basis for which lighting requirements are set.

2.1.1 Physiology of the Human Eye

This section will look at the physiology of the human eye and how each part responds to light, either reflecting, absorbing or transmitting light. It will look at the different components such as the pupil, the lens and the retina and the roles that they play in receiving and transmitting light information. The visual system can essentially be divided into two parts: the eye which forms the receptor by which light is received and the brain which processes the information it receives, extracting different elements of that information as the electric signal moves along the optic nerve (Purves & Lotto, 2003) (Boyce, 2003a). A diagrammatic representation of these two parts can be in Figure 2.1 below.

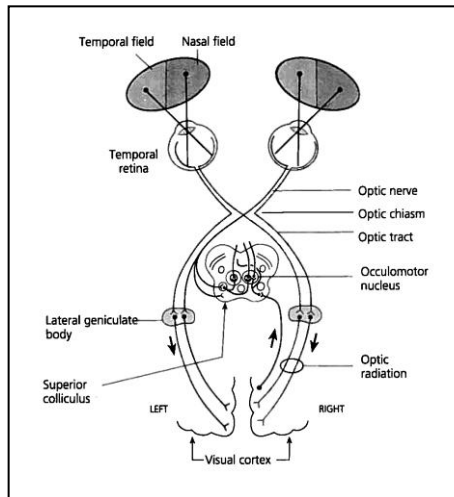


Figure 2.1: Diagram showing the connection between the eyes and the visual cortex in the brain

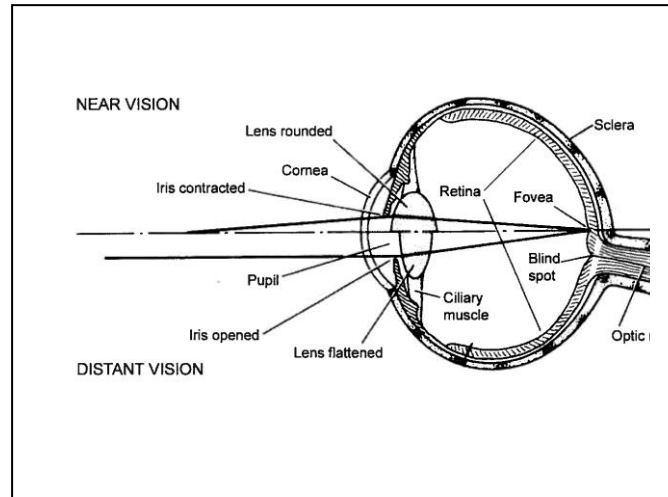


Figure 2.2: Physiological changes which occur during different types of vision (Boyce, 2003a)

The eye is made up of 3 layers. The outer layer or sclera is the protecting layer, allowing the eye to maintain its shape under pressure and although its surface is mostly white, at the front of the eye it becomes transparent and creates the cornea. This is the area through which light enters the eye. The second layer is the choroid which is made from blood vessels which transport vital oxygen and nutrients to the final layer, the retina. At the front of the eye the choroid separates from the sclera to form the ciliary body which in turn forms the iris. The iris has two layers, the outer layer which is pigmented and the inner which contains blood vessels. (Purves & Lotto, 2003)

The 'colour' of a person's eyes is determined by this outer layer of the iris, the level of pigment influencing the colour the iris appears. The level of pigmentation or colouring of the eye can often have an impact on the sensitivity of the person to light intensity. The iris forms the circular opening or pupil which is the point at which light is allowed to enter the eye. The size of the pupil can be altered to control the amount of light that enters the eye and reaches the retina as shown in Figure 2.2, but as described in Boyce (2003a) it is also altered by other factors such as the age of the person or emotions such as fear and anger. This physical response to emotion is an indication that the eye is connected to other parts of the brain that are not involved with the visual system as highlighted by Rautkylä et al (2012) in their recent paper.

These individual characteristics of the eye, such as the colour of the iris, affect the light transmittance achieved and therefore any impact it has on physical response including a connection with an emotional response. This in turn means that the eye and the way it performs have an innate impact on the visual response of each individual person.

After passing through the pupil the light reaches the lens which although fixed can change focal length by changing its size. Beyond the lens light passes through the vitreous humour, a transparent jelly-like fluid, finally reaching the retina where it is absorbed and sent as signals to the brain. The retina is formed of 3 layers; a layer of multiple photoreceptors where the light is absorbed, the deepest part of the retina, a layer of collector cells which form the link from the photoreceptors to the final layer of ganglion cells, the axons of which form the optic nerve. Once the light has reached this point it is sent as electrical signals to the brain via the optic nerve, in essence the retina is therefore an extension of the brain.

Investigations into the visual system have shown that there are four types of photoreceptor within the retina and they can be grouped into two; rod and cone photoreceptors. Rod cells are all the same with the same photopigment therefore having the same spectral sensitivity, but there are three types of cone cell, short, medium and long (S, M, L) each with its own specific spectral sensitivity. S, M and L denote the part of the visible spectrum that the cone cell is most sensitive to and as such they differ in response to one another.

Rod and cone cells are also different in terms of their location across the retina. Rod cells are found towards the outer edge of the retina outside the visual axis and therefore provide human peripheral vision. Cone cells, or photoreceptors, are concentrated at the centre of the retina or fovea which lies on the visual axis with a small percentage of cone receptors around the rest of the retina. The distribution of the three types of cone cells is also not the same with the majority of L and M cones within the fovea and receding towards the edge of the retina. The S cones are in higher density just outside the fovea also reducing in number towards the edge of the retina. The ratio of S, L and M cone photoreceptor cells is 32:16:1 (Walraven, 1974). Figure 2.3 below shows the different spectral sensitivities of the three cone photoreceptors cells.

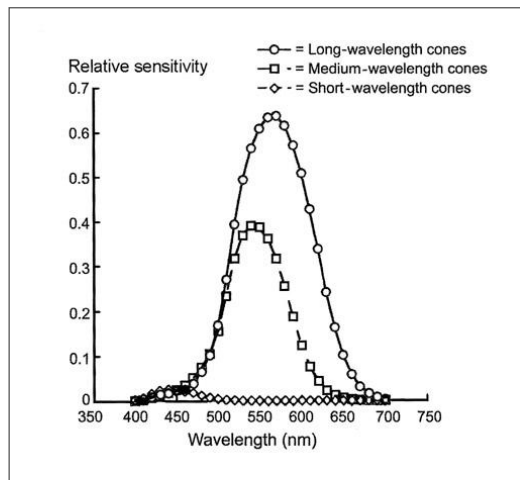


Figure 2.3: Graph showing the spectral sensitivities of the 3 photoreceptors (Boyce, 2003a)

The brain needs to receive these messages from the eye to understand and locate the body within its surroundings. As noted by Michel (1996) the light that is received at the retina reveals all the physical shapes, colours, textures and reflections of surfaces in the built environment that are then sent as messages to the brain. It is therefore important to provide an environment within buildings which maintains the performance of the visual system, the focus of numerous guidance documents (BS EN 12464-1:2011, 2011) (BS 8206-2:2008, 2008) (CIBSE, 2012).

2.1.2 Visible spectrum and the sensitivity of the visual system

The visible part of the electromagnetic spectrum ranges from 400nm to 800nm which sits between the Ultraviolet at one end and the Infrared at the other. This range is defined by the response of the human visual system, but the different photoreceptors are more sensitive to certain parts of the spectrum than others as shown above in Figure 2.3. The sensitivities of the human visual system to light can be described as three different types of vision; photopic, scotopic and mesopic directly related to combinations of photoreceptors that are operating in response to specific lighting environments.

The spectral sensitivity of photopic response that defines the main activity of our visual system based around the photoreceptors in the fovea where the majority of photoreceptor cells are L and M cones. Each of these photoreceptor cells has its own spectral sensitivity; L cones peak sensitivity at 560nm and M cones at 530nm. A luminous efficiency function has been derived for photopic response with peak sensitivity at 555nm based on the involvement of these two cells. The scotopic luminous efficiency function dominated by the sensitivity of the rod photoreceptor cells which are described by peak sensitivity of 496nm and sit mainly outside the visual axis. Scotopic vision peaks at a slightly shorter wavelength than that of photopic,

around 507nm. Mesopic response defines a balance of response from both the rod and the cone photoreceptors and for this reason is harder to define.

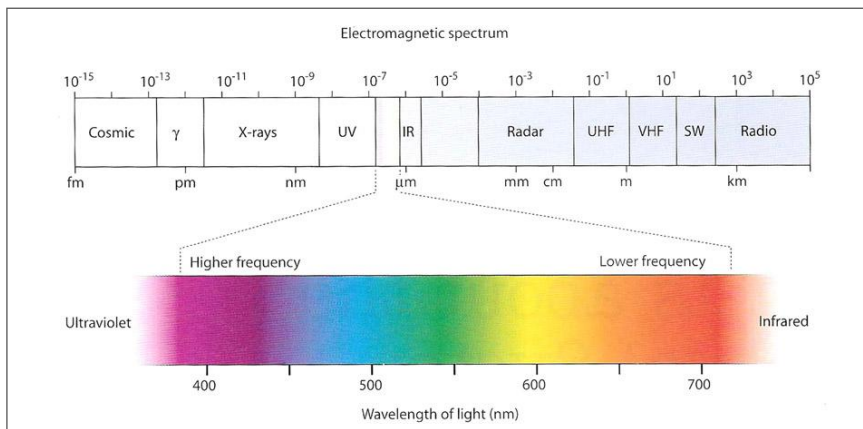


Figure 2.4: Electromagnetic spectrum showing visible spectrum in more detail taken from Purves & Lotto (2003)

It is widely accepted that the peak sensitivity for the human visual system is focused on the photopic and is around the yellow-green band of the spectrum, approximately 555nm and most lighting systems provide enough luminance so that the visual system is working mostly in the photopic. In order for there to be a uniform understanding of the relative luminous efficiency functions of various light sources the CIE (Commission Internationale de l'Eclairage) has established three different spectral sensitivities; CIE Standard Photopic Observer, CIE Modified Photopic Observer, CIE Standard Scotopic Observer shown in Figure 2.5. As Boyce (2003a) notes it is also important to acknowledge that they are designed to measure light and not to give a precise description of the operation of visual system.

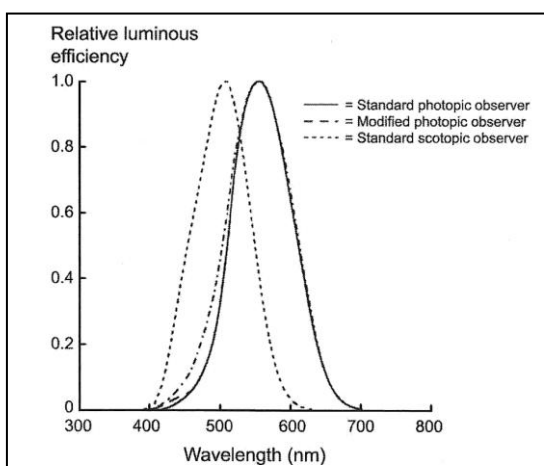


Figure 2.5: Relative luminous efficiency functions for the various CIE Standards taken from Boyce (2003a)

The three different cone pigments and their peak sensitivities indicate that they are sensitive to different colours of light and show maximum absorption to this wavelength of light; S cones to blue light, M cones to green light and L cones to red light. Light from at least two photopigments must be received by the brain in order for the brain to detect any colour vision. Very simply described, with normal colour vision a blue light is seen when the blue-sensitive cones are more strongly stimulated than the red or green-sensitive

cones. Some people are described as colour blind when one or more of these photopigments is not present and a very small percentage of people only have rod cells in their retina and therefore cannot distinguish any colour at all.

The broad spectral sensitivity of the three types of cone photoreceptor and one rod photoreceptor within the retina suggests that the performance of the human visual system is affected more by the quantity or intensity of light than the specific wavelength of light. Each photoreceptor covers a wide range of wavelengths as well as overlapping each other to a certain degree therefore it is possible for humans to carry out most visual tasks under a wide range of lighting environments. The detection of colour within visual stimulus is the only task performance that is significantly affected by the spectrum of light. (Boyce, Hunter, & Howlett, 2003)

2.1.3 Visual response to the quantity of light

As summarised in the report by Boyce, Hunter & Howlett (2003) identified above, the visual system does not necessarily need light stimulus to come from daylight. The main factor for the successful performance of the visual system is the intensity of light falling on the visual task. The human visual system can respond to a wide range of light intensities ranging from 0.000001 cd/m^2 which might be experienced during a dark night with light from the stars to $100,000 \text{ cd/m}^2$ which could occur on a brightly sunlit day. This is represented in Figure 2.6.

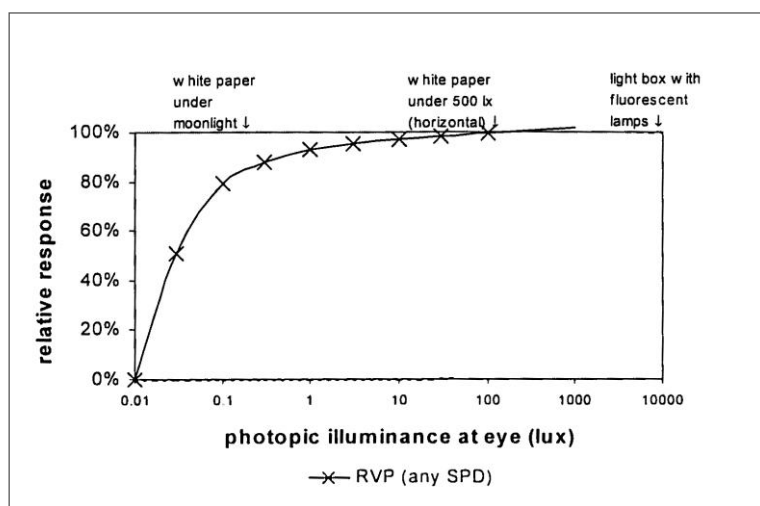


Figure 2.6: Relative visual performance of the eye across a range of illuminance levels taken from (Rea, Bullough, & Figueiro, 2002)

Rod and cone cells also respond differently to the quantity of light received. Based on illuminance at the retina, different combinations of photoreceptors respond to light stimulus. Rod photoreceptors are still active when light levels are low whereas cone photoreceptors

become active when greater amounts of light fall on the retina which is why objects appear clearer in a brightly lit room. Research into the physiology of the eye has shown that visual acuity, the ability of the eye to determine fine detail, improves as illuminance on a specific surface increases with the cone photoreceptors responsible for detecting colour and detail. This is also why humans need to move their eyes to provide more detail information about objects that are in their peripheral vision, initially only picked up by the rod photoreceptors.

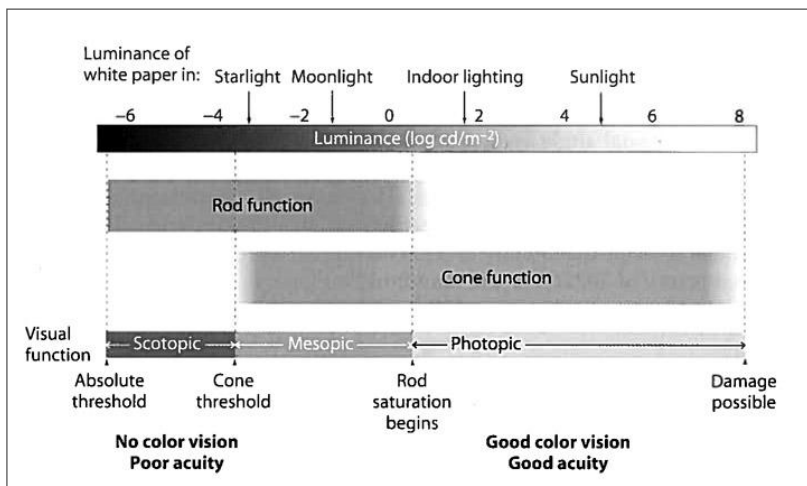


Figure 2.7: Luminance levels at which the eye can operate identifying the ranges over which both the rod and cone cells are effective taken from Purves & Lotto (2003)

As shown in Figure 2.7 photopic vision describes when the cone photoreceptors are mostly operating and is generally when luminance is higher than 3 cd/m^2 . In these environments the eye can detect colour and detail information from the surroundings. Scotopic vision describes when light levels are so low that only the rod photoreceptors can detect light information and the visual system does not pick up any colour information or detail. Scotopic vision occurs when luminance levels drop below approximately 0.001 cd/m^2 . As the cone photoreceptors are not sensitive to these low levels of stimulation, vision is dependent on the rod photoreceptors. In this state detail and to a greater extent colour are not perceived, just shades of gray.

Mesopic vision is the intermediate between the photopic and scotopic conditions between 0.001 and 3 cd/m^2 . In this state both cone and rod photoreceptors are working to varying degrees. During a gradual decline in luminance the rod cells gradually take over from the cone cells which results in a gradual deterioration in colour vision and a shift in sensitivity to shorter wavelengths.

It is evident from all this information that the rod and cone photoreceptors have significantly different sensitivities. The rods are much more sensitive to light than the cone photoreceptors, picking up light information at low levels of illuminance. They are also more sensitive to light at shorter wavelengths than the cone photoreceptors. These differences in sensitivity affect the way the eye responds to the different lighting environments they are exposed to.

Much investigation has been carried out to define the amount of light needed to perform a variety of visual tasks. A widely accepted range of illuminances have been suggested within guidance and standards for the built environment from industry bodies such as the Chartered Institute of Building Services Engineers (CIBSE). These guideline illuminance levels are generally followed by the majority of designers and engineers and are often specified as the requirement for building interiors. They range from 300-500lux for desktop tasks such as reading and detail work to 50-100lux for stairways and corridors. They are driven by a range of factors including health and safety and productivity. A range of these recommended lighting levels are outlined in Table 2.1.

Table 2.1: Recommended lighting levels for a variety of lighting scenarios (reproduced from SLL Code of Lighting)

Type of area, task or activity	Lumens/m ² (lux)
General areas within buildings	
Circulation areas and corridors	100
Offices	
Writing, typing, reading	500
Technical drawing	750
Educational buildings	
Classrooms	300
Auditorium, lecture halls	500

Research by Muck and Bodmann, 1961, discussed by Boyce (2003a) looked at the comparison of optimum lighting for performance and lighting conditions that people found comfortable. On the surface it seemed to show that although above 2000lux the subjects in the experiment found the lighting conditions uncomfortable their level of performance in the visual task continued to improve. This suggests that lighting discomfort may not be directly linked to performance however there were concerns raised by Boyce that other factors relating to laboratory tests such as an increased sense of motivation may have had an impact on the results. This motivation may have been different had they been carrying out the task in a

normal environment. Boyce makes the point that it is important to provide a lighting environment which permits performance of the visual system but also avoids discomfort which can be difficult as visual performance is determined by the physiology of the eye whereas discomfort can be linked to the person's expectations. A lighting environment which is deemed uncomfortable due to the fact that it has not met the expectations of the user may still be adequate for visual performance.

2.1.4 Adaptation of the visual system to light

Luminance as well as spectral sensitivity plays a role in the performance of the human visual system and the response of the different photoreceptors. The eye adjusts to the prevalent lighting conditions, to the amount of light being received by the eye, reducing the sensitivity and increasing the detail differentiation when there is a lot of light but increasing the sensitivity and reducing the detail differentiation when the light level is low. This adjustment is called adaptation and it is a process that is continuously happening within the eye. The eye has to be able to adapt to a wide variety of illumination, and it does this by physiological adaptation using the pupil to limit or maximise the amount of light that passes into the eye as well as neural adaptation which is triggered at moderate light levels.

The eye also uses photochemical adaptation which happens within each individual photoreceptor. Dark adaptation describes the process that occurs when moving from a very brightly lit environment to one which is very dark or lit with low levels of illuminance. It takes the eye a number of minutes to be able to distinguish objects and features within this space and adaptation can take 20-30mins. As Purves & Lotto (2003) describe this type of adaptation relies on the restoration of the biochemical integrity of the rod cells as rhodopsin, the photopigment within rod cells is bleached by light. If this process happens in reverse, in other words moving from a dark environment to a lighter one or light adaptation, adaptation occurs much more quickly.

Although the human visual system has a wide range of adaptation, being able to respond to wide variety of lighting environments, it is sometimes considered that the therefore the source of this light does not matter significantly to the performance of visual tasks. However, the quality of the lighting environment has been identified to have an impact on human performance, even if this is indirectly, relating to a person's perception of the environment.

2.2 Lighting design guidance

As described above light is defined as the range of the electromagnetic spectrum to which the human eye is sensitive. An internationally accepted system of photometry has been developed to measure and quantify this light as defined by the sensitivity of the human visual system. In response the lighting industry has developed light sources for all possible practical scenarios from reading, operating micro machinery to driving a range of vehicles. This has also included the development of equipment to measure and analyse the lighting environments created. Although there are no laws that protect the inclusion of daylight within buildings there are a number of guidance documents and standards which provide support to architects and lighting designers. However the metrics and defined requirements have not significantly altered over the last 25-50yrs.

2.2.1 Daylight metrics

The daylight factor was developed in the UK in the early twentieth century as a means of defining the daylight requirements of building interiors. Although there have been minor modifications the basis for this metric remains the same. The Daylight Factor (DF) describes the percentage of daylight at a given point (normally the horizontal plane) within an internal space in comparison to the available external illuminance; essentially given as a ratio of the total amount of daylight illuminance falling on a horizontal plane to the total horizontal illuminance from the sky vault at the same time. It is described in the Equation 2.1,

$$DF = (E_i/E_o) \times 100\%$$

Equation 2.1: Daylight Factor equation

where:

E_i is the daylight illuminance at an internal point on a working plane;
 E_o is the simultaneous daylight illuminance on a horizontal external plane from an unobstructed hemisphere of overcast sky.

DF is a useful metric to provide a simple evaluation of the effectiveness of a daylight design at an early stage particularly when using physical models or when used retrospectively to assess the performance of existing buildings with photometers or lux meters. The outcome is also simple; the higher the percentage the more daylight is provided within the space. The internal illuminance or E_i is the sum of three components; direct light from the sky visible at the given internal point or sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC). This calculation is typically repeated for a number of

points within the internal space from which a contour map is often created to graphically represent the distribution of daylight across the space. Although this metric uses relative rather than absolute values its ability to give a good indication of the daylight distribution within a room is still valued.

Average daylight factor is a derivation of the original point calculation which provides an assessment of the average illuminance from daylight over a specified surface area. This calculation is based on the total amount of light falling on a surface and then the fraction that is transmitted to the next surface, the surface illuminance is defined by the total light received divided by the surface area. This calculation essentially provides the mean daylight factor across the surface area specified, typically the horizontal working plane. In simple terms as described by Tregenza and Wilson (2011) the illuminance at any given point within an internal space is calculated by multiplying the illuminance on the window by the window area and then dividing it by the interior surface area.

The Building Research Establishment (BRE) formula for calculating the average daylight factor shown below in Equation 2.2 (Building Research Establishment, 1986), has simplified the process by including the rule of thumb $\theta/2$ for the window daylight factor and ρ^2 for overall mean reflectance rather than splitting it between upper and lower surfaces.

$$D = \frac{\theta T A_w}{(1 - \rho^2) A_r}$$

Equation 2.2: BRE Average Daylight Factor formula (Building Research Establishment, 1986)

where:

- θ is the angle subtended by the visible sky (degrees) measured in a vertical plane normal to the glass from the geometric centre of the window;
- T is the diffuse transmittance of glazing including the effects of dirt;
- A_w is the net glazed area of the window in m^2 (the net area of glazing is the area of windows less any lost to glazing bars or window frame);
- ρ is the overall mean surface reflectance value;
- A_r is the total area of internal surfaces.

In the equation above, A_w is the net glazed area of the window in square meters and A_r is the total area of the ceiling, floor and walls including windows also in square meters. This equation has also been shown to provide a means of calculating the necessary window area above the working plane to achieve a given daylight factor by inverting the equation as outlined in BS 8206-2:2008 (British Standards Institute) and shown below.

$$A_w = \frac{DA_r(1-\rho^2)}{T\theta}$$

Equation 2.3: Equation to calculate window area necessary to achieve a given Average Daylight Factor (British Standards Institute, 2008)

Although the Average Daylight Factor metric only provides a static assessment of the available daylight within an internal space it does offer a good initial assessment of the effectiveness of a design on the daylight provided. However it can cause potential problems due to the fact that it is purely based on an overcast sky and does not factor in any contribution from direct light from the sun. Even so it remains an element within the requirements of daylight performance within lighting and environmental standards and regulations for buildings.

2.2.2 Legal requirements

There are no statutory requirements in the UK for a particular illuminance level provided by daylight other than those that form part of the Workplace Regulations 1992 relating to Health, Safety and Welfare; Regulation 8 states that ‘every workplace shall have suitable and sufficient lighting’ as well as that it ‘shall as far as is reasonably practicable be by natural light’. There is also a statement relating to the control of daylight penetration onto the working plane within the Health and Safety Regulations 1992 which states that ‘windows shall be fitted with a suitable system of adjustable covering to attenuate the daylight that falls on the work station’. The provision of lighting and more specifically daylight is covered almost indirectly in a number of other regulatory documents such as the Building Regulations in reference to the impact on the performance of the building as a whole.

2.2.2.1 Building Regulations

Although there is no specific regulation relating to the provision of daylight within new or existing buildings the inclusion of daylight design is indirectly affected by certain parts of the Building Regulations. This is particularly relevant when considering Part L of Schedule 1 relating to the *Conservation of fuel and power*.

Guidance for satisfying this regulation in new buildings other than dwellings is provided in Approved Document L2. The requirement from Schedule 1 states that *Reasonable provision shall be made for the conservation of fuel and power in buildings by; limiting heat gains and losses and providing fixed building services which are energy efficient and have effective controls* (DCLG, 2013). In terms of the provision of daylight within buildings and therefore the

specification of windows requirement L1(a) is most relevant and specifically part (i) which defines limiting heat loss through thermal elements and other parts of the building fabric.

As glazing components typically have poor thermal performance this regulation draws particular attention to this part of the building fabric. To satisfy all five criteria of this regulation the performance of the chosen glazing systems and therefore the specification have to be carefully controlled both as an individual component as well as the contribution to the performance of the building as a whole.

To satisfy compliance with the energy efficiency requirements set out in Part L, the calculated CO₂ emission rate of the building (BER) must not be greater than the Target CO₂ Emission Rate (TER). The TER is the minimum energy performance requirement expressed in terms of the mass of CO₂ emitted per year per m² of the total useful floor area defined in Criterion 1. This must be calculated by using a tool approved by the Secretary of State such as the Simplified Building Energy Model (SBEM) or other approved tools. This calculation is based on a notional building of the same size and shape with specified properties set out by NCM Modelling Guide some of the key components of the notional building specification are shown in Table 2.2. The resultant CO₂ emissions of this notional building provide the TER. This is a mandatory part of the requirement of demonstrating compliance.

Table 2.2: Summary of concurrent notional building specification taken from Approved Doc L2A (DCLG, 2013)

Element	Side lit or unlit (where HVAC spec is heating only)	Side or unlit (where HVAC spec includes cooling)	Toplit
Roof U-value (W/m ² .K)	0.18	0.18	0.18
Wall U-value (W/m ² .K)	0.26	0.26	0.26
Window U-value (W/m ² .K)	1.6 (10%FF)	1.6 (10%FF)	N/A
G-Value (%)	40	40	N/A
Light transmittance (%)	71	71	N/A

It is also necessary for the individual building components to meet reasonable standards of energy efficiency although this is only statutory guidance rather than mandatory. The approved document states that this criterion is included so that there are limits on design flexibility to discourage inappropriate trade-offs such as including renewable energy systems to off-set the poor thermal performance of particular building fabric elements such as glazing. It is likely that if the building meets the TER requirements set with the notional building

specification then it will also meet the individual building component requirements. An example of these specification requirements are shown in Table 2.3.

Table 2.3: Limiting fabric parameters in Approved Document L2A

Element	U-value (W/m ² .K)
Roof	0.25
Wall	0.35
Floor	0.25
Windows, roof windows, roof-lights, curtain walling and pedestrian doors	2.2

There is also a specific requirement that the building must have appropriate passive control measures in order to reduce excessive solar gains set out in Criterion 3. To satisfy this requirement it is necessary to demonstrate that the cumulative solar gains through glazing across the period from April to September inclusive are not greater than for one of the reference glazing systems. For example for spaces that are defined as side lit the reference is an east-facing facade with full-width glazing to a height of 1m with framing of 10% and a g-value of 0.68. The focus of this requirement as stated in the approved document is to limit the need for air-conditioning or at least reduce the installed capacity of an air-conditioning unit. It is applicable to all buildings whether they are air-conditioned or not. Providing a naturally ventilated design does not satisfy the requirement to prove that the internal environment will be satisfactory for the occupant.

As is evident from the above the Building Regulations are focused on energy efficiency and a reduction in excessive heating and cooling loads. This means that the spotlight is placed on the performance of the building envelope and in particular the window or glazing system due to the fact that it is often the worst performing building component in terms of thermal resistance. Driving towards a reduction in energy consumption can, in many instances, result in a reduction in the area of glazing within a building facade.

2.2.2.2 Rights to Light

Similarly to the laws of ancient Greece and Rome which protected a properties access to natural light the Right of Light is an easement which exists under the Prescription Act (1832) and protects the landowners' right to receive light through apertures within their property. This right usually occurs once a 20 year period of light being received through the aperture has passed. The right of light is covered under civil law and is separate from any planning permission and can often be overlooked with new developments, this right can sometimes

prevent construction or result in the demolition of a new building (Law Commission, 2013). The basis of this law and its relationship with planning development is currently being considered by the Law Commission. Depending on the outcome it may change the way that these rights are acquired and the remedies to infringements that are available to the courts.

The 50:50 rule is typically used as a measurement to assess the light levels within a room interior as part of a right-to-light case; it involves calculating the percentage of a room's area that can receive adequate light levels. This is not considered to be the amount of light that was previously received within the room but a percentage of that light. The measurement is generally taken at the height of a working plane, approximated at 850mm, and any point on this plane that is considered to receive 0.2% of the total illumination received from the sky is deemed to be adequately lit. This utilises the sky factor, a similar metric to the daylight factor. When less than 50% of the room at this level receives 0.2% of the total illumination from the sky it is deemed to cause an injury to the occupier.

2.2.3 Design guidance

Although there are not any specific regulatory requirements for the provision of daylight within buildings there are a number of guidance documents and standards that often act as 'requirements' which the architect or lighting engineer are expected to satisfy. Based on knowledge of the visual system and how it responds to light and research undertaken to better understand the performance of a variety of tasks under different lighting scenarios illuminance levels as well as other technical aspects of a lighting environment have been defined.

2.2.3.1 British Standards

Since 2002 the British Standards Institute (BSi) have provided a number of standards that provide guidance and recommendations for the provision of lighting environments based on the recommendations set out by the Committee for European Standards (CEN). There is a particular standard that relates to daylight which is covered by BS 8206-2:2008 Lighting for buildings – Part 2: Code of practice for daylighting (British Standards Institute, 2008). There are other standards that also provide guidance for lighting design such as BS EN 12464-1:2011 Light and lighting – Lighting of workplaces – Part 1: Indoor workplaces (British Standards Institute, 2011).

BS 8206-2:2008 acknowledges within the *aims* and *criteria for design* that daylighting design is more than providing task lighting that it contributes to how people experience the spaces within buildings they inhabit, that it provides interest and variety as well as being connected to

the provision of a view. It does notes amongst these other contributions the connection of daylight to the regulation of the circadian system as well as the proposed link with Seasonal Affective Disorder (SAD). The majority of this code of practice for daylighting focuses on the evaluation of daylighting design and simple calculations to assess the provision a particular building or part of a building will provide. It separates daylight between the provision of sunlight and skylight defining the very different attributes offered by each as well as acknowledging that duration is a key parameter when evaluating the success of daylighting design.

Clause 5.5 states that the average daylight factor should be used as the measure of general illumination from skylight and that in order for a building interior to provide a predominantly daylit appearance an average daylight factor of 2% should be achieved. It also states that if a space provides an average daylight factor of at least 5% then supplementary electric lighting will not normally be needed. Clause 13 and 14 provide calculation methods for the average daylight factor and daylight illuminance respectively. Beyond providing minimum average daylight factor values for different spaces within dwellings where it plausible to go below 2%, BS 8206-2:2008 refers to other lighting guidance such as BS EN 12464-1 (British Standards Institute, 2011) and the Society of Light and Lighting Code for Lighting (CIBSE, 2012) for specific lighting requirements for different tasks relating to quantity and quality.

Although this British Standard acknowledges the benefits that daylight can provide within a building interior beyond task illumination, its main focus is providing criteria for the satisfactory provision of daylight and the methods which can be used to satisfy these criteria. It also provides a series of recommended and approximate values for certain calculations such that standard assumptions can be made including the mean light transmittance of glazing materials and maintenance factors. These figures allow for the reduction in daylight transmittance due to a series of factors.

The role of the specification of glazing systems and its impact on the light admitted to the interior space is briefly acknowledged within this document. In clause 5.8 outlining criteria related to the contrast between the interior and the view outside the impact of tinted glazing on the amount of daylight admitted to the interior as well as affecting the colour perception. It is noted that the distortions caused by tinted glazing can go unnoticed by the building occupant particularly if the window with tinted glazing provides the main source of lighting. The use of 'traditional' low transmittance glazing is also mentioned in reference to improving internal solar gains due to excess penetration of direct sunlight. The British Standard

acknowledges that these types of glazing can reduce the quantity of daylight that reaches an interior space as well as reducing solar gain. The availability of a few 'new' types of glazing using coatings which can provide high daylight transmittance as well as lower solar gain is also noted but this is the limit of the information provided in this area with the focus being mainly on different types of shading devices.

2.2.3.2 Society of Light and Lighting: Code for Lighting

Since the British Standards Institution (BSI) adopted the lighting recommendations set out by the Committee for European Standards (CEN) which provide the quantitative requirements for a wide range of lighting environments the Codes for Lighting produced by the Society of Light and Lighting (SLL) provide more of a guide for interpreting the standards. SLL was preceded by the Lighting Division of the Chartered Institution of Building Services Engineers (CIBSE) and the Illuminating Engineering Society (IES) and their Codes for Lighting were the guides typically used by the lighting industry. The most recent SLL Code for Lighting (CIBSE, 2012) focuses on the three areas relevant to lighting design; review of all lighting recommendations and how to interpret them, description of the calculations for quantitative lighting design and the effects of lighting on building occupants including task performance, perception and health.

The SLL Code for Lighting provides a comprehensive guide to all lighting recommendations for a wide range of applications both within the building and outside including road lighting. Chapter 5 which focuses on Daylight is mostly taken from the British Standard Code of practice for daylighting (BS 8206-2:2008) as well as referring to technical guidance in SLL Lighting Handbook (2009) and SLL Lighting Guide 10 (1999). The other benefits of daylight are acknowledged within this guide such as the potential affect on mood and perception of space as well as the health benefits and the connection between light and Seasonal Affective Disorder (SAD). It also notes the role of light with the regulation of the circadian system suggesting that higher levels of daylight within buildings are important for those people that are unable to go outside on a regular basis such as hospital patients or the elderly. Even though it does not include quantitative or qualitative requirements it does acknowledge that it is important for people to receive higher illuminance levels during the morning in order to regulate their circadian system. This provides very little guidance, more along the lines of a cautionary note.

In terms of the specific performance of windows there is not a substantial amount of guidance as to the affect of different glazing types. It does note that tinted glazing can have an effect on the occupants perception of the internal space, often without them realising it which can

cause problems when colour rendering is important. It also notes that studies have found that if the transmittance of glazing falls below 25% a significant proportion of people find the view out unacceptable. Overall it does acknowledge that unless there is a specific functionality which requires the exclusion of daylight it should appear to be the dominant light source within an interior space. The balance between daylight and electric light is emphasised in reference to control as well as mixing light from these two sources. It is often the case that horizontal task illuminance is provided or at least supplemented by electric light but the space should still appear to be daylight, providing awareness of the change in light throughout the day as well as its gradation across a room.

2.2.3.3 BREEAM Assessment

The environmental assessment method (BREEAM) developed by the Building Research Establishment (BRE) for buildings provides a rating of the building performance both at design stage as well as completion. It is driven by energy efficiency and sustainable design with the majority of credits being awarded for energy and water management as well as material specification. Visual comfort is one of the assessment criteria included within the Health and wellbeing section with a small number of credits available. Although glare control and daylight provision make up the majority of the credits in this section there are also credits for providing a view out as well as appropriate internal and external lighting provision.

The assessment of whether there is adequate daylight provision is based on two methods; average daylight factor or average daylight illuminance levels. These are both driven by the requirements of visual performance and uniformity with the average illuminance values typically 300lux and specified for the horizontal plane. There is an indication that improved lighting provision might have a positive impact on a building occupant's well-being as the requirement for inpatient accommodation in hospitals is greater than most other internal spaces at Daylight Factor value of 3. This may be driven by the fact it is considered that people in these spaces may spend a greater percentage of time inside than people with more normal daily patterns.

The daylight factor required in most occupied spaces is set as 2% across a minimum area of 80% with exception of inpatient areas in healthcare buildings. This assessment method does not define the specific location of the 80% area which is significant when considering the drop off as the distance from the window wall increases. For example if the 80% area was calculated from the window wall the required daylight factor would be easily achieved in comparison to the area being calculated from the wall furthest from the window. This

difference makes the assessment ambiguous. To achieve the credits using the daylight factor values it is also necessary to achieve the other requirements relating to uniformity of light distribution across a given space. This can be achieved either by providing a uniformity ratio of 0.3, or at least 80% of the room has a view of the sky from a desk or table height.

If using the average illuminance method it is necessary to achieve both the average daylight illuminance which is averaged over the entire occupied space as well as the minimum daylight illuminance at the worst lit point. The hour requirements do not define when within the year that these illuminance levels need to be achieved this is shown in Table 2.4. In particular, with reference to an educational environment which has a requirement for 2000 hours per year it is likely a fair amount of the summer months these spaces will not be used at a time when the available external illuminance will be at its greatest. It may be more relevant for the requirement to also be defined by building use profile.

Both these sets of requirements are based on the illuminance levels that are achieved on the working plane; this does not take into consideration the lighting requirements for anything other than visual performance. Glare control and uniformity of daylight across occupied spaces are the key drivers for the requirements on design as well as the inclusion of appropriate user controls. Whilst these are important factors for the functional use of building interiors and the management of energy consumption they do not take into consideration the light that the eye receives for any other physiological process. Even in the simple fact that the measurement of light levels is taken at the horizontal working plane will not provide an accurate picture of the light that reaches the occupants eye.

Table 2.4: An extract from BREEAM Space type and daylight illuminance requirements (both criteria should be met) taken from BREEAM UK New Construction Technical Manual (BRE Trust, 2014)

Area type	Credits	Minimum area to comply	Average daylight illuminance (averaged over entire space)	Minimum daylight illuminance at worst lit point
Education buildings				
Pre-schools, schools, further education (occupied spaces)	2	80%	At least 300 lux for 2000 hours per year or more	At least 90 lux for 2000 hours per year or more
Higher education (occupied spaces)	1	60%		
Higher education (occupied spaces)	2	80%		
Healthcare buildings				
Staff and public areas	2	80%	At least 300 lux for 2000 hours per year or more	At least 90 lux for 2000 hours per year or more
Occupied patient’s areas (dayrooms, wards) and consulting rooms	2	80%	At least 300 lux for 2650 hours per year or more	At least 300 lux for 2650 hours per year or more

The assessment tool guidance also provides information relating to maximum room depths for various window head heights acknowledging the correlation between room size and position as well as the size of the window in terms of the resulting distribution of daylight. This is shown in Table 2.5.

Table 2.5 BREEAM maximum room depths for varied room widths, window head heights and reflectance values taken from BREEAM UK New Construction Technical Manual (BRE Trust, 2014)

	Reflectance (RB)					
	0.4		0.5		0.6	
Room width (m)	3.0	10.0	3.0	10.0	3.0	10.0
Window head height (m)						
2.5	4.5	6.7	5.4	8.0	6.8	10.0
3.0	5.0	7.7	6.0	9.2	7.5	11.5
3.5	5.4	8.6	6.5	10.4	8.1	13.0

2.3 Occupant response to daylight design

It is possible to describe what light is through scientific terms but it is the impact and associated response of the people who receive the light which is important. Beyond being a key component of the tools used by most architects to create inspiring internal spaces, light is a necessary requirement of the built environment. To live and work within buildings requires light to perform all manner of daily tasks but what if the human body needed light for more than just visual tasks. As Behling & Behling (2000) suggest that physiology and the way information about the surroundings is perceived by the senses are directly linked to human psychology.

2.3.1 Performance and productivity

Occupant preference for natural light rather than artificial light within interior spaces is well established (Finnegan & Solomon, 1981; Farley & Veitch, 2001) as well as investigations that show lighting quality can have an impact on performance, comfort and satisfaction of occupants at work (Veitch & Newsham, 1998; Aries, Veitch, & Newsham, 2010). Some studies have also investigated the impact of lighting on internal environments in residential buildings and occupant satisfaction (Aries & Zonneveldt, 2004).

A literature review of over 60 studies undertaken in this area between 1965 and 2004 provided a good summary of the outcomes of much of the investigation into occupant preference and satisfaction with lighting environments at work (Galasiu & Veitch, 2006). It summarised that the general preference by occupants was for naturally lit spaces with the belief by the occupant that it was better for well-being; one survey showing that 86% of respondents preferred daylight as a source of light (Cuttle, 1983) and another showing approximately 70% of respondents endorsing statements of the superiority of natural light (Veitch, Hine, & Gifford, 1993). The review also included some studies that highlighted the difference between people's preferences as well as an effect of the time of day, which the particular researcher speculated was the result of a physiological connection with the stimulation of the human biological clock (Begemann, van den Beld, & Tenner, 1997).

Galasiu & Veitch (2006) concluded among other things that there was a need for further investigation into a range of orientations, times of day, latitudes and seasons as well as building and window types in order to establish general recommendations for multiple locations. They summarised that a large percentage of studies into occupant satisfaction of

lighting environments have been undertaken in industrialised northern hemisphere locations and that this did not give a broad enough range of findings.

Similarly to office or working environments that are predominantly internal, the classroom has been the focus of a number of studies undertaken to try and understand the effect of the environment on the performance and well-being of children. Over a 10 year period in the 1980-90s a number of studies took place into the impact of different types of lighting on non-visual effects on school children, initially by Wohlfarth (1986) and Hargreaves & Thompson (1989) which was then replicated by Hathaway (1992). It was suggested that the different spectral output of each light could have a different impact on a variety of processes such as height and weight gain, attendance levels and achievement.

Although not conclusive the results did suggest that there was a positive connection between both the full spectrum light and full spectrum light with UV enhancement and non-visual processes within the body. Hathaway acknowledged that some of the observed benefits may be directly related to the age group of children within the study and noted that there needed to be further exploration to examine whether these benefits could be translated into other age groups. They also acknowledged that the test sites were based within a specific region of the northern hemisphere (49° – 54°N) which has relatively short periods of daylight between April and September. They suggested that this typically reduced exposure to UV radiation and may have made the children more susceptible to the benefits of a relatively small amount of exposure.

The Heschong & Mahone Group have contributed significantly to this body of research with their studies into the impact of daylight on human performance (1999) (2003a). Their work looking at the internal environment of a classroom and in particular the lighting has shown that there is a strong link between the daylight within a classroom and the children's performance. Their initial study undertaken in three different districts in USA with performance data from a total 21,000 students showed highly significant effects of the positive impact of daylight on pupil performance. In one district the results showed that the students exposed to the most daylight progressed 20% faster in maths and 26% faster in reading across one year than those students exposed to the least amount of daylight in their classroom. They were also able to show that those children in classrooms with the largest window area progressed quicker than those with the smallest.

The following study published in 2003 (Heschong Mahone Group Inc, 2003a) analysed the performance data of over 8000 students in maths and reading. Their results showed that the windows and therefore the lighting quality were a key factor in learning having both positive and negative impacts on performance. In particular it showed that a pleasant view out of a window that includes human activity and vegetation as well as objects in the distance supported improved performance outcomes. However it also showed that when teachers did not have control of the windows there was a negative effect on the performance of students, potentially related to excess glare and solar heat gain.

This finding is supported by a more recent study led by Peter Barrett at Salford University (Barrett, Zhang, Moffat, & Kobbacy, 2012) which provided a holistic evaluation of primary school classrooms and the impact on student performance. Although this study incorporated a range of design features and analysed their combined impact on the student it did show significant correlation between aspects of the lighting environment and pupil performance. Those classrooms that provided natural light from two orientations were shown to have a positive impact on the performance of the students.

2.3.2 Physiological impact

Acknowledged by a number of authors on lighting and design (Robbins, 1986) (Evans, 1981) human beings evolved under the full spectrum light provided by the sun and it is against this that other light sources are compared. As Webb (2006) states, through this evolution many of the biological processes within the human body are directly linked to the information received from this light energy. Nevertheless in modern daily lifestyles most people in the developed world spend the majority of their lives within a building and a good percentage of these environments will be completely artificially supported; too far from a window to get reasonable benefit from either natural light or ventilation.

An awareness of the importance of access to natural light is often linked to the specific parts of the electromagnetic spectrum such as Ultraviolet light. For example an acknowledgment by Evans (1981) in his formative text *'Daylight in Architecture'* at the beginning of the 1980s, that peoples' typical daily routine means that the majority of their time is spent within an artificial environment which can deprive them of the health-giving aspects of natural light such as ultraviolet light.

Highlighting the 'life-giving' attributes of sunlight or direct solar beam, light at the UV end of the spectrum emphasises further the inadequacies of artificial light sources as they do not

generally provide light at this part of the spectrum. Light at this spectrum is known to cause potential harm but also to trigger the vital production of vitamin D in the human body. The physical effect of sunlight is felt by most people when they travel to sunnier climates enjoying more sunshine hours than they are typically exposed to and the improved feeling of well-being is tangible. This does not acknowledge the valuable effects of light at other parts of the electromagnetic spectrum, particularly those in the visible band.

A large percentage of the studies undertaken to date to investigate occupants' preferences and satisfaction with the lighting environment have used scale models of spaces through which the participants make an assessment. Particularly in relation to satisfaction of window size and view such as in Ne'emann & Hopkinson (1970) using a scale model does not seem the most satisfactory method. Arsenault et al (2012) acknowledge the limitation of using a scale model and the need to repeat their study with a full scale room in order to get more accurate findings. The majority of studies in this area also use survey techniques to gather data relating to occupant perception and satisfaction. These techniques are not easily able to encompass the non-visual effects of internal lighting environments due to the focus being around occupant perception which is generally driven by a visual response.

There are currently very few studies which look to examine the effect that lighting environments have on these non-visual responses.

2.3.3 Effect of glazing specification on the occupant

There have been many studies undertaken to evaluate the impact of the lighting environment on the occupants' perception and satisfaction of a given space. There have also been research findings that suggested the type of light source has an effect on the preferred light level with occupants preferring a higher illuminance level if it was provided by daylight than if provided by artificial light (Laurentin, Berrutto, & Fontoynt, 2000). This highlights the fact that people perceive the quality of light as much as whether the quantity is adequate for them to perform a specific task. Most of the investigations into the impact of internal lighting environments on the building occupant are based on spaces that have neutral glazing systems, basic single or double glazed units with clear glass, such that the focus is not on the detailed specification of the glazing system but more generally the lighting environment as a whole.

A few studies that have been published more recently start to address the different types of glazing system on the market that are becoming more common within modern buildings. Arsenault, Hebert & Dubois (2012) looked at the effects of glazing colour type on the

perception of daylight quality, arousal and the switch-on of artificial lighting. They acknowledged the need to readdress the research concerning the effect of window glazing in respect of the growing evidence of the non-visual effects of light particularly as information relating to colour-shifted light to date has focused mainly on artificial sources. This study looked to investigate three different glazing types; bronze, neutral and blue and the perception of participants of five quality factors including visual comfort, pleasantness and light level.

As Arsenault et al (2012) had hypothesised the qualitative results showed that there was a preference for bronze glazing in terms of visual comfort, pleasantness and light level in line with a previous study (Boyce, Eklund, Magnum, Saalfeld, & Tang, 1995). Arsenault acknowledged that it would be valuable to investigate glazing with darker tints in order to see more distinct effects. All three glazing types within this study provided a very similar total transmittance values (approx. 53%) such that there may not have been the necessary differences in the lighting environment. This study also only measured subjective perception of the occupant and did not include any measure of the physiological or non-visual responses to the lighting environment. It would be necessary to establish the impact of these other physical factors to truly understand the difference between the affects of these glazing systems on human well-being.

2.4 Summary and conclusions of Chapter 2

This chapter has shown that while guidance for the design of lighting environments includes recommendations for the use of daylight within internal spaces, there are no specific regulations controlling the provision of daylight within building interiors. This often results in other design parameters such as thermal performance and energy efficiency being prioritised.

It also highlighted that the system of photometry used in buildings is based on a wealth of experience about the workings of the human visual system within internal lighting environments, typically designed around a range of activity-driven illuminance levels. These lighting guidelines do not currently include any requirements based on the non-visual system which would support occupant well-being beyond visual comfort.

Research outlined above has also shown that there is a physiological connection between the building occupant and the lighting environment to which they are exposed. This has been shown specifically for environments where people spend extended periods of the day inside such as schools and offices. If exposure to light is shown to support well-being, including the quality of light and the benefits of exposure to daylight, then these recommendations will need to evolve to include guidance on lighting environments that support the non-visual system.

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Chapter 3

Methodology

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3 Methodology

This chapter outlines the research methodology of this thesis, and the methods used for the collection of data to answer the question posed; does the specification of glazing systems within modern buildings have a significant impact on the health and well-being of the building occupant? The application area of this study therefore draws together two distinct fields which have, as their basis, fundamentally different disciplines; biomedical research and building physics. This chapter will describe the methods of analysis used for both areas and how they will be brought together.

The main aim of the thesis was to establish whether the choice of glazing system could be impacting on the well-being of the building occupant based on the daylight they receive within a building interior. This requires an evaluation of whether there is a connection between changes in glazing technology and reduced light stimuli to activate non-visual physiological processes of people within buildings such as circadian rhythms. It is initially necessary to ascertain whether the connection between these non-visual responses and light stimuli is the same or different to the better understood visual system. By establishing the lighting parameters required to stimulate the non-visual system it will then be possible to analyse the performance of a range of glazing systems based on these requirements. These two aspects or stages of the thesis form the basis of the methodology.

The foundation on which the question is posed is in part an area of developing biological research; the proposition of some researchers that the presence of a 'novel' third photoreceptor within the eye connects the light received with physiological processes independent of vision. This thesis therefore follows a precautionary standpoint (Harremoes, et al., 2001), a position where a number of components of the background to the study are not conclusive but are developed to a point which warrants further investigation from complementary sectors such as the lighting and design industry. This has been acknowledged by a number of other researchers (Rea, Figueiro, Bullough, & Bierman, 2005) (Lucas, et al., 2014). This first aspect of the thesis will take the form of an intensive literature review of biomedical and neurological research will provide an understanding as to the lighting parameters necessary to stimulate non-visual processes within the human body.

Based on the proposed lighting parameters necessary to support non-visual processes, the second aspect will be to quantify the effect that material advancements and new

manufacturing techniques for the production of glazing systems are having on the quality and quantity of daylight received internally. The aim of this part of the study is to test the hypothesis that the specification of some glazing systems may be having an impact on the well-being of the occupant beyond their visual performance.

Using a case study room all these aspects can be drawn together and the implications of the different specifications of glazing on the light that is received by the occupant can be evaluated. This thesis builds on work undertaken by other researchers, in particular Arsenault et al (2012), who looked at the perceived lighting environment with user surveys to measure impact based on visual comfort, pleasantness and light level and Bellia et al (2013) who looked at the difference between vertical and horizontal illuminance based on one glazing type. The approach taken within this thesis to address this hypothesis is a mixture of analytical and applied methodology following in broad terms a quantitative approach (Fellows & Liu, 2003). The structure of the thesis is graphically represented in Figure 3.1.

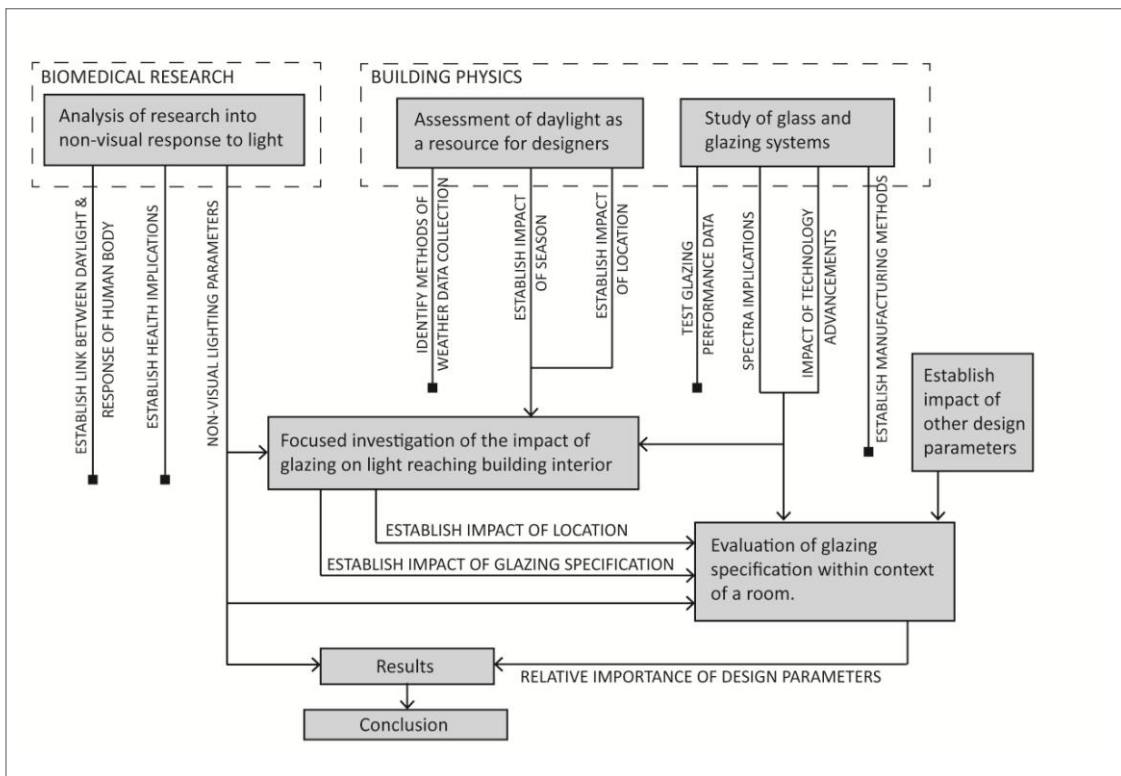


Figure 3.1: Flowchart describing thesis methodological structure

3.1 Data collection

This thesis will draw together information from three main knowledge areas; biomedical research into the physiology of the eye and non-visual responses to light, building technology through the development of glazing systems, and the methods for assessing the spectral quality and availability of daylight based on a given geographical location.

3.1.1 Extensive and systematic review of biomedical/neurological research

Seminal reviews such as those by Stevens (Stevens & Rea, 2000) and Rea at the EPRI/LRO 5th International Lighting Research Symposium (Rea, 2002a; Rea, 2002b) identified the potential health implications caused by lighting environments to which people are exposed on a daily basis, caught the attention of those beyond the biomedical community. The systematic literature review in this specific area of biomedicine will draw on the key sources reviewed within these seminal articles as well as an independent review of literature by industry experts. It will focus mainly on primary research across the biomedical and neurological research community into the non-visual effects of light stimulus on the human body. Utilising a range of medical research databases including PubMed¹, PMC² and MEDLINE³, and BioMed Central⁴, journal papers, research study reports, and conference proceedings will be evaluated against a series of criteria to establish relevance to the thesis as well as validity.

As the methodological quality of these sources is important, particularly as most are likely to be based on clinical trials, a systematic approach is taken to provide a thorough synthesis of the existing research to extract the information required for this thesis. This process identified where different studies agreed or disagreed in respect of the different parameters important to the thesis such as sensitivity to wavelength of light, quantity of light used as well as duration subjects exposed to light stimuli. The set of parameters for this systematic review is based around the following criteria;

- Physical testing scenario; either in the lab or in a live scenario
- Number of subjects
- Randomised sample or not; was the method of randomisation described?
- Double blind study or not; was the method of blinding described?

¹ PubMed is an online database created by National Center for Biotechnology Information including over 23 million citations for biomedical literature <http://www.ncbi.nlm.nih.gov/pubmed>

² PMC is full-text archive of biomedical and life sciences journals created and managed by U.S. National Institutes of Health's National Library of Medicine (NIH/NLM) <http://www.ncbi.nlm.nih.gov/pmc/>

³ MEDLINE provides citations and abstracts to biomedical journal papers from publications across the world, access is provided by PubMed.

⁴ BioMed Central is open access publisher that publishes articles from over 250 peer-reviewed journals.

- Record of type of light source used; daylight or artificial (what type of lamp if artificial)
- Detailed information regarding the light source used eg. spectral distribution, colour temperature, intensity levels
- Cited by other sources

As the biomedical research is only one aspect of this study the literature review will also evaluate and cross reference secondary research in the biomedical field as well as other relevant fields such as psychology, building physics and lighting design. This will include such peer-reviewed publications as *Lighting Research & Technology*, *Building and Environment* as well as *Interior and Built Environment* that all have a strong emphasis on holistic approach to research within the built environment. Institutions which focus on the science of lighting will also provide a good basis for understanding the human implications of lighting design such as International Commission on Illumination (CIE) and Society of Light and Lighting as part of the Chartered Institution of Building Services Engineers (CIBSE). Research institutions focusing purely on lighting research such as the Lighting Research Center at Rensselaer Polytechnic Institute, NY will also provide a valuable resource of the latest research and development in the lighting community.

The conclusion of this systematic review will be to propose a set of lighting parameters which represent the human non-visual response to light stimuli which may or may not be different to that of the visual system. This set of parameters will provide a basis from which it is possible to assess the lighting environment of interior spaces and more specifically the impact the specification of glazing has on the light transmitted.

3.1.2 Detailed performance information of glazing systems

This study will evaluate the performance characteristics of a range of glazing systems based on key attributes such as thickness, material composition including tints and applied coatings. Optical information will be extracted from the International Glazing Database (IGD) and analysed using two computer programmes created for the analysis of glass and glazing at the Lawrence Berkley National Laboratory (LBNL)⁵. *Optics6*⁶ has been developed to analyse optic properties of glazing systems and *WINDOW6*⁷ has been developed to analyse the thermal and

⁵ LBNL is Lawrence Berkeley National Laboratory based in California, USA where extensive research into daylighting and window design is undertaken as well as other scientific endeavour.

⁶ *Optics6* has been developed by Lawrence Berkeley National Laboratory and can be downloaded from the website <http://windows.lbl.gov/software/Optics/optics.html>

⁷ *WINDOW6* has been developed by Lawrence Berkeley National Laboratory and can be downloaded from the website <http://windows.lbl.gov/software/window/window.html>

optical performance of different windows. These two pieces of software are freely available for researchers and designers to use in the analysis of the performance of glazing systems.

Both *WINDOW6* and *Optics6* software use as a default the International Glazing Database which provides the properties of an extensive range of glazing systems from different manufacturers. The data provided for each glazing system within *Optics6* and *WINDOW6* is reductive, based on measurements of the response of each glazing system to a given light source which makes it possible to compare the performance of different glazing systems. The default spectral weighting function (SWF) used within the *WINDOW* software is the National Fenestration Research Council (NFRC) approved standard ISO/CIE 9845 (ASTM E892) which is derived from a direct spectrum. There is currently uncertainty as to which spectrum is the most technically correct standard. As the LBNL guidance on Standards for Solar Optical Properties of Specular Materials suggest it is difficult to say that one spectrum is better than another for all possible conditions⁸.

3.1.2.1 Physical testing of glass samples

One of the uncertainties for a designer when specifying building components including glazing systems are the accuracy of the information provided by the manufacturer. In particular detailed spectral distribution information of light transmittance is not regularly provided for glazing products by manufacturers. In order to establish confidence in this dataset, physical testing of a series of glazing samples using a laboratory grade spectrometer will be undertaken. This will provide detailed information about glazing performance characteristics, more specifically detailed spectral distribution of transmitted and absorbed wavelengths of light. This information will provide a means by which to compare the information provided by the International Glazing Database.

Spectrometry is the qualitative measurement of the reflection or transmission properties of a material as a function of wavelength. This can be carried out using the full spectrum of light energy but is normally limited to near ultraviolet, visible and near infrared spectrum. A spectrometer can measure intensity of light energy as a function of the light source

⁸ The latest information on LBNL website <http://windowoptics.lbl.gov/data/standards/solar> suggests there are at least four standard based on the use of spectrometers to measure the spectral solar optical properties of glazing including ISO 9050 which uses global spectrum ISO CIE 9845 from ASTM E892, NFRC uses the direct spectrum of ISO/CIE 9845 from ASTM E891, EN 410 which uses the CIE 98 global solar spectrum as well as NFRC_300 which is a potential development of NFRC standard. NFRC recently voted in favour of a new global spectrum ASTM G197 but implementation has been deferred.

wavelength. It uses a standard light source which provides energy across the chosen part of the spectrum to pass light through a material sample.

A Fourier Transform Infrared (FT-IR) Bruker VERTEX 80v Spectrometer (BRUKER OPTIK, 2006) based within the Physics Department at Cardiff University will be used to test a series of glazing samples. This spectrometer uses a similar technique to a single beam spectrometer allowing all frequencies across a given spectrum range to be measured simultaneously. The FT-IR technique can be used to collect data from the visible and ultraviolet parts of the spectrum by altering the chosen light source to provide the necessary beam. The light source used by the spectrometer is a tungsten halogen lamp which provides a visible/near infrared source of light suitable for these tests.

The FT-IR technique utilises an optical device called an interferometer which produces a signal which has information about all the frequencies within it. The interferometer employs a beamsplitter which divides the incoming beam into two beams; one is reflected off a fixed mirror, the other reflected off a mirror which is fixed to a mechanism making small oscillating movements. A calcium fluoride beamsplitter will be used for this series of glazing tests as it is the most suitable material for the visible spectrum. These two beams meet at the beamsplitter and interfere with each other to create an interferogram within which information about every frequency of light from the source is carried. Before the beam reaches the interferogram it passes through an aperture which controls the amount of energy that passes through the sample and therefore the amount of energy that reaches the detector. The size of the aperture can be altered and will determine the overall intensity of the frequency spectrum. The aperture size set for this series of glazing sample tests will be 4-6mm.

The spectrometer also contains a detector to capture the light that is transmitted through the chosen material sample. A silicone detector will be used for these glazing sample tests as they are the most suitable for detecting the visible spectrum. This information then needs to be interpreted into a frequency spectrum (intensity vs. frequency). This is achieved using the Fourier transformation technique which is performed by OPUS software on the computer connected to the spectrometer.

The frequency spectrum output from each glazing sample test will be used to compare with the same information extracted from the *Optics6* programme created by LBNL which utilises optical information provided from the International Glazing Database. As mentioned above,

this information will establish confidence in the dataset provided by the International Glazing Database.

3.1.2.2 Choice of glazing samples

The range of potential glazing samples which could be included in this study might reach into the thousands based on the variety of component options available but it is not realistic to evaluate all of them as part of this study. Instead a selection of glazing types has been chosen for analysis which provides a representation of the broad range of glass and coatings available similar to sample sets devised for other studies (Gueymard & duPont, 2009). These specimens are grouped into seven general categories; Coating/Film on clear pane glass, Body tinted glass, Laminates or laminated glazing, Double glazing – Low-E, Double glazing – Specialist solar control, Triple glazing and Quadruple glazing.

In order to choose glazing systems within these categories a number of factors were used in the selection process. Firstly, in order to understand the impact of a glazing system within current building environments it was important to include a proportion of the glazing systems typically specified by architects. Secondly, it was also important that the range of specimens included a number of glazing systems from major manufacturers. Thirdly, the range of specimens needed to include specimens that were at the extremes of certain performance factors, such as the highest transmittance value. The range of samples also included a broad selection of light-to-solar gain (LSG) ratio values in order that it included glazing samples that were highly spectrally selective. A number of samples included in the Gueymard study (2009) were also included in this study for reference.

In order to make some comparisons across the range of glazing systems analysed using the LBNL *WINDOW6* software it is necessary to make some assumptions relating to the core information used within this software. Assuming a generic spectrum based on global irradiance ensures that all the glazing systems can be compared within these parameters. The *WINDOW* software also calculates thermal and optical properties based on centre-of-glass which excludes the effect of edge and spacer, these values may affect the U-value of the glazing system but they do not affect the visible transmittance. All values used in this analysis will be based on a centre-of-glass calculation.

It is also worth noting that all glass thicknesses are stated as their nominal values rather than actual as these measurements vary slightly from product to product. The study does include

an assessment of the affect of thickness of glass particularly when looking at body tinted glass where it is proposed to have the greatest impact.

The positioning of the coatings and films within the range of specimens is dependent on the specific manufacturer and the material used to form the coating. The position of the coating or film was noted for each sample with an 'F' denoting front and 'B' denoting back. The optical properties of each sample collated as part of this study includes total solar and visible transmittance as well as reflectance and absorptance of visible light. It will also include u-value and solar heat gain coefficient in order to calculate light-to-solar gain ratio.

The full database of optical information of this range of glass and glazing is included in Appendix A whilst specific information will be included within the main body of the thesis.

3.1.3 Available external illuminance data

The quality and quantity of daylight that reaches any internal environment, as well as being affected by the filtering of the glazing system will fundamentally depend on the available external illuminance at the chosen location. Utilising climate data from a range of global locations as well as knowledge relating to the spectral qualities and variability of external illuminance study will assess the impact of the global and local context of a building and the impact this may have in terms of the specification of glazing.

External illuminance data will be extrapolated from climate data provided by the European Database of Daylight and Solar Radiation recommended by British Standard for lighting for buildings BS8206-2:2008 (British Standards Institute, 2008). *SATELLIGHT*, an online resource of Daylight and Solar Radiation data, uses images taken from Meteosat type geostationary satellites located above the equator at an altitude of 36,000km from where it can see one half of the Earth's surface. Using this method overcomes some of the limitations of collecting measurements from the ground is by computing radiation data from satellite images taken of the Earth's surface. Satellites offer a good source of data as they provide extensive and regular measurements of the Earth's atmosphere. From the images, reflected radiation is measured in three spectral bands; visible 0.5-0.9 μ m, water vapour 5.7-7.1 μ m and IR 10.5-12.5 μ m. Each pixel of the image covers a specific area of the Earth's surface from South to North poles, the area covered by a pixel ranges from approximately 5km in longitude by 6km in latitude in North Africa (34°N) to approximately 5km in longitude by 16km in latitude over Scandinavia (64°N).

There are a number of methods for estimating the global radiation at ground level from satellites (Cano, Monget, Albuissou, Guillard, Regas, & Wald, 1986), more information about this source of climate data will be given later in the thesis. This data will be used to establish the availability of external illuminance based on time of year and geographical location across the Northern Hemisphere.

3.2 Analysis of data

As biomedical and neurological research into the non-visual response of the human ocular system to light is incomplete there is no agreed model to define circadian efficient lighting. Therefore two approaches are used to analyse the data within this thesis. Initially a set of proposed lighting requirements for the non-visual system are used to undertake an analysis of the effective performance of a range of glazing systems based on total visible transmittance. This is undertaken based on external illuminance data for different geographical locations in order to assess whether global location should be taken into consideration in the specification of glazing systems to provide an internal environment that supports occupant well being. This initial analysis will provide information about the illuminance level at the internal surface of the glazing system.

As this initial analysis is only relevant in terms of light received at the eye if the building occupant was stood at the window facing out it is then necessary to establish the relationship between the light available at this surface and what is typically available within the rest of the room. As this is dependent on a wide range of factors based on the design of the chosen room it is necessary to use a Case Study example from which some general assumptions can be made.

3.3 Case Study

Although the main focus of this thesis is the effect of glazing specification and not to evaluate the impact of the design of a space on the distribution of light, in order to draw together the various aspects of this thesis it is necessary to apply them to a Case Study room. This will provide the means to establish the impact of the range of glazing systems on the light received by the building occupant. Although there are a wide variety of design decisions made which could influence the distribution of light within this Case Study room, this thesis will use a standard room as a basis from which to assess the effect of a range of glazing systems.

The case study room will be single aspect and of a standard width and depth in order to simplify as many of the other potential variables as possible in terms of their effect on the distribution of light. By establishing a Case Study room with a range of assumed positions at which people may be seated will provide the means to evaluate the light that is actually received at the eye of a person inhabiting this room. Horizontal and Vertical illuminance measurements will be taken at a range of points within the room. As explained above this

thesis is focused on the impact of glazing specification and not the effect of complex spatial design on lighting distribution therefore a simple, orthogonal room is most appropriate. The physical attributes of the room will be measured to provide an accurate record of the internal space.

The measurements taken within the Case Study room will be used to calibrate a computer generated model of the room created with modelling software *Autodesk 3d Max Design* so that a comparison of a range of different glazing types can be made. By using this model it will also be possible to establish the impact of the geographical location and whether more consideration needs to be made when specifying glazing systems in particular locations.

3.4 Recap

This chapter has outlined the methodology used within this thesis as well as the areas of data collected and the manner in which it has been analysed. The application of this data to a Case Study will establish whether the choice of glazing system is likely to have a significant impact on the light received by the building occupant.

As was also summarised in Chapter 1, the following is a brief summary of the Chapters within this thesis and how they address the aim and hypothesis.

Chapter 1: Why light is important to architecture and the people that inhabit buildings

Chapter 2: The human visual system and current guidance for designing with natural light

Chapter 3: Methodology

Chapter 4: Non-visual response to light and the implications for daylighting design

Chapter 5: The natural resource of daylight: what is available and how to evaluate

Chapter 6: The role of the glazing system and how it affects the light received within buildings

Chapter 7: Initial evaluation of the specification of glazing and light received internally

Chapter 8: Case Study: The light that reaches the occupant

Chapter 9: Results: The combined evaluation of all parameters and the impact on daylight received at the eye

Chapter 10: Conclusions

Chapter 4

Light and non-visual processes

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4 Light and non-visual processes

Following on from Chapter 2 which described the response of the human visual system to light stimulus this chapter will discuss the inherent connection between light and the physiology of the human body and the role the eye plays beyond the visual system. Acknowledging the different components of the human visual system and how they respond to different lighting environments introduced in chapter 2 it will look at the other effects that light stimuli have on the body. Research undertaken in the last two decades has highlighted the neural connection between the eye and other important physiological processes within the human body.

This chapter will examine research undertaken in the fields of biomedicine, neuroscience and chronobiology which identifies the potential differences between the visual and the non-visual systems. This research will provide the basis for looking at lighting characteristics that will offer the most appropriate lighting environment for both our visual and non-visual systems. This chapter will also cover some potential health implications of poor lighting environments within which many people live and work and how a better understanding of the effect of light might alter the way our buildings are designed.

Since the 1980s scientists have started to show that the eye performs non-visual functions within mammalian physiology. As Provencio (2011) describes, the eye is the sole receptor for light received by the human body and fundamental to many physiological processes. It is therefore important to first understand the physiology of the eye and how the visual system works so that we can then understand the differences between this and the other functions of the eye. This chapter will look in detail at what the research identifies as the differences between physiology supporting visual and non-visual systems and how they respond to light stimuli.

4.1 Light at the eye

Our eyes perceive luminance, the light that an object or surface produces, either directly or through reflection rather than illuminance which is the amount of light falling on that object or surface. The light that is received by the eyes is often described as corneal illuminance. In terms of describing the interior spaces people inhabit it might therefore be more relevant to know the vertical illuminance rather than the horizontal even though this is more typical for guidance and standards as outlined in Chapter 2. This measure has been derived by an emphasis on illuminating a particular task but taking into consideration that the eye may perform a role beyond visual performance it could be as important to know the amount of light that reaches the retina; the point at which light information is transferred to the brain.

The amount of light reaching the eye is likely to be significantly less than measured on a horizontal surface within the same space due to reflection and absorption of the surrounding surfaces (Aries, Begemann, Tenner, & Zonneveldt, 2003). Many guidance documents for the design of lighting environments refer to the amount of light that falls on a given surface or illuminance levels for various activities but these may not take into consideration the amount of light reaching the eye. For example as Rea (2002a) comments in his symposium presentation, the recommended lighting level to perform many visual tasks is often given as ~300-500lux on the horizontal working plane which can be equated to approximately 100lux at the eye. These recommendations may not have such relevance to the quantity of light needed to stimulate other non-visual processes as they are a measurement of illuminance taken on a horizontal plane rather than the amount of light reaching the eye. As Middleton et al (2002) note this measurement of light stimulus is even further from retinal illuminance.

How much light actually reaches the eye is a question that a piece of research undertaken at the Lighting Research Centre by Bierman, Klein & Rea (2005) set out to investigate using a prototype device called the *daysimeter*. The device was designed to analyse the different parameters which define light stimulus for the human circadian system; quantity, wavelength, spatial distribution, timing and duration or length of exposure. The fact that head and body movements affect the light which reaches the eye or retina was also taken into consideration. Using two sensors attached to the head of a subject at a similar height to the eye it recorded both photopic with a broad range of wavelengths and circadian or 'blue' light, which was a smaller range below 570nm with peak sensitivity of 470nm. Initial findings showed interesting results relating to the different lighting environments that contribute or affect the circadian system throughout the day and night as well as the difference in light received from natural

and artificial sources. For example in a seating position facing a north-facing window in an artificially lit room the sensors from one test subject reported 1000lux from the photopic sensor whereas 3000lux from the circadian or 'blue' sensor. The recorded illuminance levels dropped to ~150lux for both sensors at various times when the subject moved further into the interior of the same room. As the authors note this highlights the important difference in spectral distribution of light sources as well as the significant effect of a person's position within an interior space. This research underlines the fact that there is more to lighting technology than meeting recommended levels of illuminance on a horizontal plane, if the lighting environments we provide are to support more than just the visual system. In order to get an accurate picture of the light that reaches the retina it is important to understand what might modify this stimulus such as head and eye movement, eye closure and light transmission through the eye itself (Brainard, Rollag, & Hanifin, 1997).

Other researchers have identified this difference between the horizontal plane and the eye when taking light measurements. Stevens and Rea (2000) describe the amount of light entering the eye as retinal illuminance in reference to the part of the eye that ultimately collects the light. They express retinal illuminance in Trolands (T) which is defined by the equation shown **Error! Reference source not found.**

Equation 4.1: Equation defining the amount of light entering the eye or corneal illuminance reproduced from Stevens & Rea (2000)

$$T = A_p E \rho / \pi$$

where;

A_p is pupil size (mm^2)

E is illuminance striking the surface being viewed (lux)

ρ is directional reflectance of the surface toward the eye

It is not very common to see light measurements recorded in these units, as Stevens & Rea (2000) state; most often the published data estimating the effects of radiation received at the eye is only available in illuminance values. Illuminance levels do not take into consideration these other factors such as pupil size therefore the inaccuracy of this measurement has to be acknowledged.

The physiology of the eye itself, the health and ageing of this organ, can also play a part in the amount of light information that is received by the brain. Research into the development or deterioration of the eye has shown that an initial thickening of the lens occurs generally

between 10 to 25yrs of age. During this period the amount of UV light transmitted decreases significantly (Lerman, 1987). The study by Lerman also showed further decreases from approximately 47 years of age, in particular the light transmitted at the shorter wavelengths of the visible spectrum. This thickening of the lens means that there is a reduced amount of light being collected by the retina, with a specific effect on the shorter wavelengths of the visible spectrum.

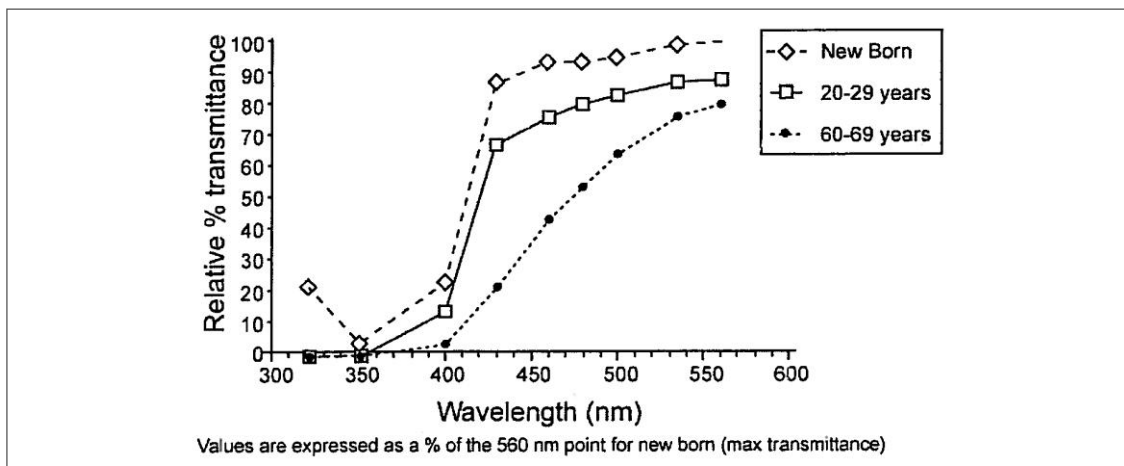


Figure 4.1: Graph showing the lens transmission characteristics of the normal ageing eye (taken from CIE (2004) after Brainard (1997))

This deterioration in transmittance of shorter wavelengths has also been seen in younger people where the aging of the lens has an impact. For example, Brainard et al (1997) showed that there was a 45% reduction in the light transmission at 420nm compared to 460nm. This reduction in transmission with age is shown in Figure 4.1 above. This suggests that even at a young age the brain may not receive all light information at specific parts of the spectrum available within the environment.

These investigations show that it is therefore important to consider both vertical illuminance within a space as well as the horizontal illuminance on a given working plane. This will provide a more accurate picture as to the light that might be reaching the eye of a person within an interior space. It is also worth considering that what reaches the cornea may not provide an accurate picture of the light that is received at the retina due to the age and health of the eye itself. This may be more difficult to ascertain as it is subjectively dependent for each individual occupant. However it would be plausible to assume that for those spaces inhabited by a greater percentage of older people, such as elderly care homes, the illuminance levels should be increased to compensate for likely deterioration of the lens transmission within this age group.

4.2 Non-visual processes and the eye

Through evolution the human body's physiological systems have been designed to perform in an environment with an abundance of full spectrum light energy from the sun. Physiological functions have developed in order that the body can respond to changing environmental conditions for example; sweat glands create moisture on the skin which acts as an evaporative cooling system. Human physiology is an interactive function which responds to the environment around it. The connection between sensory stimuli and the physiological mechanisms in the body was outlined in a presentation by Gappell (1995) relating to what she describes as *Psychoneuroimmunology*. It acknowledged the importance of photobiology, the design of the lighting environment to go beyond functionality and visual performance. Gappell describes the potential health benefits of daylight as specific organ systems are sensitive to light or are 'light-modulated' having evolved under the influence of the full spectrum of light from the sun. The review also acknowledges work by Wurtman (1975) which makes the statement that after food, light is the most important stimulus for the human body in order to control physiological functions.

This section will look at light as an external trigger for other processes within the body and the importance of the connection between the eye and the brain. Using evidence from a growing body of research into the role the eye plays as a receptor for non-visual processes it will look at how light effects certain parts of the brain and in turn a number of physiological processes such as the sleep/wake cycle, core body temperature and the release of hormones to the rest of the body. If these processes are affected by the characteristics of the light that is received at the eye then this light stimuli will in turn have secondary health implications. This further emphasises the need to consider the design of the lighting environment for more than visual performance.

4.2.1 The eye and the brain

The eye is a sophisticated organ that allows people to interpret the world around them but it is the connection between the eye and the brain that completes the visual system. The light that is collected by the photoreceptors within the deepest layer of the retina is sent via the retinal ganglion cells to the brain as electrical signals along the optic nerve. These electrical signals received by the visual cortex, the part of the brain where vision occurs, are processed as information about our surroundings. Along this path the optic nerves from each eye are brought together at the optic chiasm where they are rearranged and extended to the lateral

geniculate nucleus. Along the way some of the information collected at the retina is diverted through optic nerve fibres to other parts of the brain, for example the superior colliculus which is located at the top of the brain stem, the part of the brain responsible for controlling eye movements (Boyce, 2003).

The lateral geniculate nucleus as well as relaying electrical signals from the retina to the visual cortex also receives information from the reticular activating system. This is a part of the brain stem that determines the general level of arousal and it has been shown in some studies (Livingstone & Hubel, 1981) that a low level of arousal leads to attenuated visual information being sent to the visual cortex. This suggests that the visual system is linked to other physiological or even psychological processes within the body and that light information collected by the retina is adjusted depending on other hormone levels present in the brain. This research suggests that the eye may be connected to multiple systems within the human brain not just the visual system. It also highlights the importance of holistic studies which encompass more than one input of information to fully understand how the eye and brain work together.

Since the 1980s research studies (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980) (Brainard, et al., 1988) (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000) have also shown that there is a connection between the eye and the suprachiasmatic nuclei in the hypothalamus, the centre of the human circadian system or the internal clock (Aschoff, 1981; Klein & Moore, 1979). The retinohypothalamic tract (RHT) projects from the human retina into part of the brain which controls a large number of basic physiological processes. These include metabolism, reproduction and hormone regulation as well as processes as memory and emotional response. These neural connections are shown in the diagram in Figure 4.2. The suprachiasmatic nuclei are a pair of hypothalamic nuclei which are understood to be key components of the biological clock or circadian system. This research identified the eye as a key organ involved in not only the visual system but also in other significant physiological processes controlled from the hypothalamus. It also reinforced the theory that light could be the main external cue for these physiological processes within the human body.

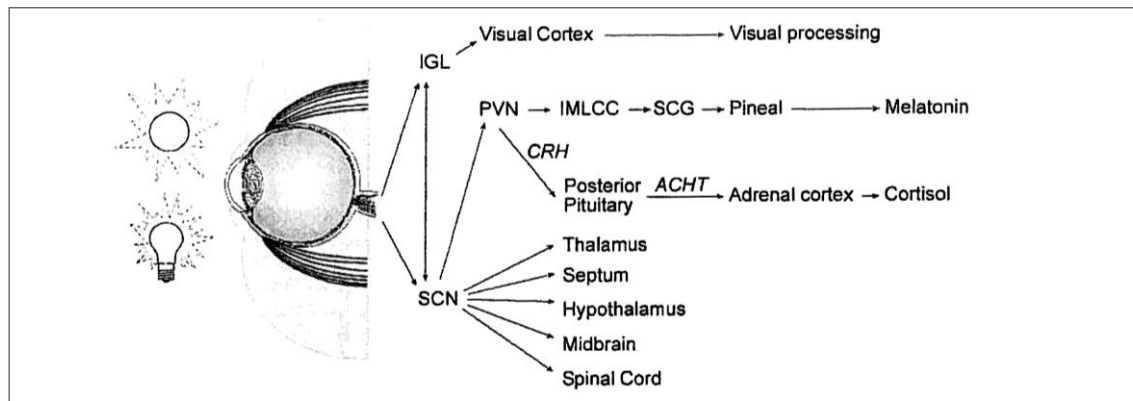


Figure 4.2: Image of the connection between the eye and the brain taken from CIE (2004)

4.2.2 Physiological processes linked to the eye

Human physiological processes have developed under full spectrum light received at the eye therefore it is likely that non-visual responses are influenced by light as an external trigger, but the detailed characteristics of the light stimuli are not as clear. The connection to the internal regulator or biological clock within the brain indicates that the information collected by the eye influences the signals that are sent to the rest of the body and in turn the response of other bodily functions. These other physiological processes include the suppression of hormones such as melatonin and cortisol, circadian cycles such as body temperature, sleep and wakefulness as well as ultradian cycles such as heart rate and thermoregulation.

4.2.2.1 Circadian cycle synchronisation

Circa meaning approximate and *diem* or *dies* to mean day suggests that the circadian rhythm describes the body's natural diurnal cycle also called the body clock. Although the human circadian system is endogenous and will continue without external cues, like all other mammals it relies on exogenous or external triggers to maintain connection with the local context. It is evident then that it is connected to many daily processes within the body such as sleep patterns and core body temperature. It had initially been believed that circadian entrainment was a result of social interaction (Aschoff, Fatranska, Giedke, Doerr, Stamm, & Wisser, 1971; Wever A. R., 1970) as well as others external cues such as food intake and activity levels (Wever R. A., 1979), it is now widely accepted that light is the main exogenous cue for the human circadian system (Czeisler, Richardson, Zimmerman, Moore-Ede, & Weitzman, 1981) (Wever, 1983) (Czeisler, et al., 1989) (Boivin & Czeisler, 1996). The human circadian system is connected to a number of other biological processes beyond the timing of the sleep/wake cycle such as eating times, core body temperature, hormone production and cell regeneration. The human circadian or biological clock has a phase of approximately 23.9-

24.5 hours, just out of sync with the 24 hour day/night cycle. Exogenous or external cues are therefore necessary to entrain the human circadian system to the local 24 hour day/night cycle.

The circadian system or 'body clock' is reset every morning in line with the day/night cycle with exposure to light, described as phase-resetting. Depending on whether the individual has a naturally 'fast' or 'slow' cycle, described by their chronotype, will influence when they are most susceptible to light stimulus (Roenneberg, Wirz-Justice, & Mellow, 2003). Without this daily phase resetting (shortening and lengthening) human sleep/wake patterns would gradually shift completely out of time with the day/night cycle and be in a state of free flow. This sensitivity to light stimulus was clearly identified by research with subjects who have been deprived of all external time cues such as studies of those that have lost both eyes (Czeisler, et al., 1995). In this study the subjects were not able to entrain their circadian rhythms and their sleep/wake cycles deteriorated into free flow suggesting that light received at the retina of the eye was needed as an external trigger. Figure 4.3 taken from Boyce (2003) graphically describes the entrained and free flowing sleep/wake cycles of an individual over 25 days, the black shading representing the periods of sleep. From day 6 onwards the subject is exposed to a constant dim light throughout the 24h period and the circadian cycle extends to 25h in a state of free-run which results in a steady shift of sleep period.

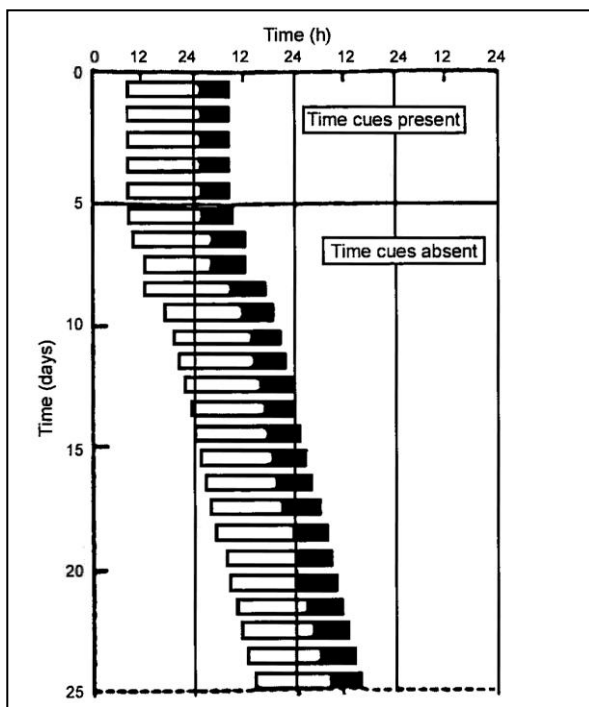


Figure 4.3: diagram/graph describing entrained and free-flowing circadian systems taken from Boyce (2003)

An explanation of the effect of light on the human circadian system is underlined by the description of the Kronauer model (Kronauer, Forger, & Jewett, 1999; Forger, Jewett, & Kronauer, 1999) which shows human sensitivity to light exposure in relation to phase shifting or synchronising the circadian system. This mathematical model, developed in line with empirical data, offers a means of defining a quantifiable effect of light stimuli on the human circadian system based on a series of factors such as the intensity and duration of exposure to light. This model emphasises the power of external light stimuli to drive circadian phase-shifting, such that without this external trigger it would default to its endogenous or natural cycle, just out of sync with the 24h day.

This research suggests the possible effects of a desynchronised circadian system where the cycle of melatonin production from the pineal gland might be affected by this free-running state. Rea et al (2002) suggests this would mean that melatonin would be released at the wrong times of day resulting in lethargy and drowsiness as well as other symptoms caused by mistimed activity of organs which are regulated by melatonin. They also suggest that uncommon interruptions of light can also shift the phase of the circadian cycle forwards or backwards, possibly desynchronising it with the day/night cycle. This response often occurs during trans-world travel or night-shift work, as the light signals are out of sync with the timing of the biological clock. An increasing amount of research has been carried out to produce positive outcomes from carefully timed light exposure, which could for example enhance wakefulness and therefore productivity during a night shift.

Further research has indicated that the circadian system is formed of a two oscillator mechanism (Warman, Dijk, Warman, Arendt, & Skene, 2003; Wehr, Aeschbach, & Duncan Jr, 2001). One mechanism is more responsive to phase advancing light stimuli and is connected to melatonin offset, described as the M (morning) oscillator. The second mechanism is more responsive to phase delaying light and is connected to melatonin onset, described as the E (evening) oscillator. Findings from studies looking at the effect of light on melatonin regulation have shown differing results for melatonin onset and offset suggesting that these two mechanisms do not necessarily give a parallel response to light stimuli. This differential response to light at the beginning and end of the subjective night has been suggested as the mechanism which allows the human circadian system to respond to the changing daylength between seasons (Wehr, Aeschbach, & Duncan Jr, 2001). It also suggests that lighting requirements for the buildings people inhabit may need to take into consideration different characteristics at different times of the day as a result of this dual oscillator mechanism.

4.2.2.2 Hormone regulation - melatonin

The connection or neural pathway between the eye and the suprachiasmatic nuclei (SCN) is the retinohypothalamic tract (RHT). This sends non-visual light information received at the eye to the hypothalamus, central clock of the brain as shown in Figure 4.4. This part of the brain controls a number of physiological functions of the body such as metabolism, reproduction, core temperature and hormonal release. This system regulates delivery of a large percentage of hormones around the body such as cortisol. Research has also shown that it has a direct impact on the regulation of melatonin, the hormone that is connected to the sleep/wake cycle. The paraventricular nucleus (PVN) of the hypothalamus sends photic information to the pineal gland which in turn regulates the secretion and suppression of melatonin. Melatonin is most evident in the body during the night and has been described as the “hormone of darkness” as it creates the feeling of drowsiness before the onset of sleep. It can also be taken in its chemical form as an oral supplement to help encourage sleep particularly during international travel when the body might be ‘out of sync’ with daily timings.

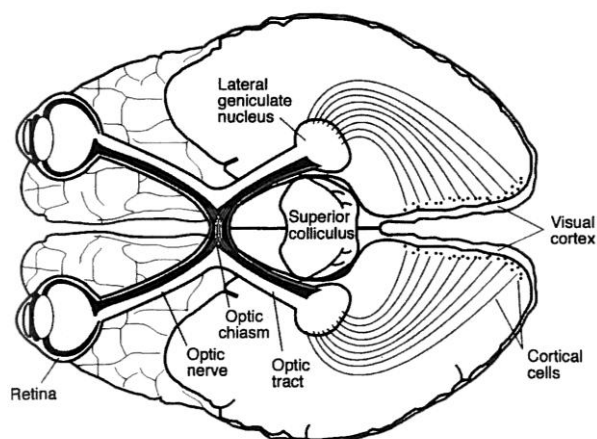


Figure 4.4: Schematic of eye-brain pathways (Boyce, 2003)

Due to the presence of melatonin in the body during night time and not during the day it is inextricably linked to circadian phase-setting. Research has shown that suppression of the hormone melatonin can occur if light stimulus is received at the eye (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980) (Brainard, et al., 1988) (McIntyre, Norman, & Burrows, 1989) with these studies being undertaken during the subjective night, the time at which this hormone is present in the body. Lewy et al (1980) produced the first findings which indicated that melatonin suppression has an acute sensitivity to light. They tested subjects using a higher illuminance than previous studies and showed significant suppression of melatonin levels in

the blood and unlike other animal species it returned quickly to darkness levels once the subject was no longer exposed to the light stimulus.

As the effect of light stimuli can clearly be observed through the recorded level of melatonin within the blood it has often been used as the key indicator of the impact of light on the non-visual system. A number of these studies have also shown that there is a dose-response relationship between illuminance levels and the suppression of melatonin (Brainard, et al., 1988) (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000) as well as sensitivity to the wavelength of light received (Thapan, Arendt, & Skene, 2001) (Brainard, et al., 2001b). The effect of light stimulus on the suppression of melatonin, like the synchronisation of circadian cycle, is also linked to the timing and duration of exposure. The visual system has a quick adaptation to changing lighting environments due to the different characteristics of the rod and cone cells. As the non-visual system is not thought to use the same neural pathway it may not have the same adaptation characteristics, this could have an impact on the amount of light that needs to be provided by an internal lighting environment as a large percentage of the population spend most of the daylight hours inside.

The presence of the steroid hormone cortisol in the human body also follows a circadian rhythm, reducing throughout the day to its nadir before habitual bedtime and increasing again throughout the night until its peak just before habitual wake time (CIE, 2004). This endogenous cycle happens irrespective of actual sleep and wake times although it is influenced by a wide variety of external factors such as; anxiety and stress, physical activity, blood sugar levels and sleep loss. The regulation of cortisol is controlled by the hypothalamus-pituitary-adrenal axis. There is ongoing investigation to establish whether this system is also influenced by external stimulus of light. A study by Jung et al (2010) was the first to show that bright light (approx. 10,000lux) administered during the ascending and decreasing phases of the cortisol circadian cycle reduces cortisol levels. They suggest that this finding is consistent with some but not all other studies and that this might be due to differences in intensity, duration and timing of light exposure, factors that influence the effect on other human circadian rhythms. They concluded that the findings suggest that light stimulus can affect the human adrenal gland such that there is neural connection between the eye and this part of the brain. Although there currently is no definitive threshold for intensity or duration this further highlights the potential affect of light stimulus on human physiology.

4.2.2.3 Core Body Temperature

Research has shown that light also has a more immediate effect on some non-visual processes shown by its effect on core body temperature as well as suppression of melatonin (Badia, Myers, Boecker, Culpeper, & Harsh, 1991). There are other biological markers used to establish the effect of light stimulus on the human circadian system such as core body temperature. The nadir or lowest point of core body temperature occurs when the level of melatonin within the body is at its highest in the middle of the subjective night. Human circadian rhythms are connected and overlap with each other throughout the 24 hour cycle; the graph in Figure 4.5 below gives a graphical representation of the rise and fall of four circadian rhythms illustrating the differences and relationships between them.

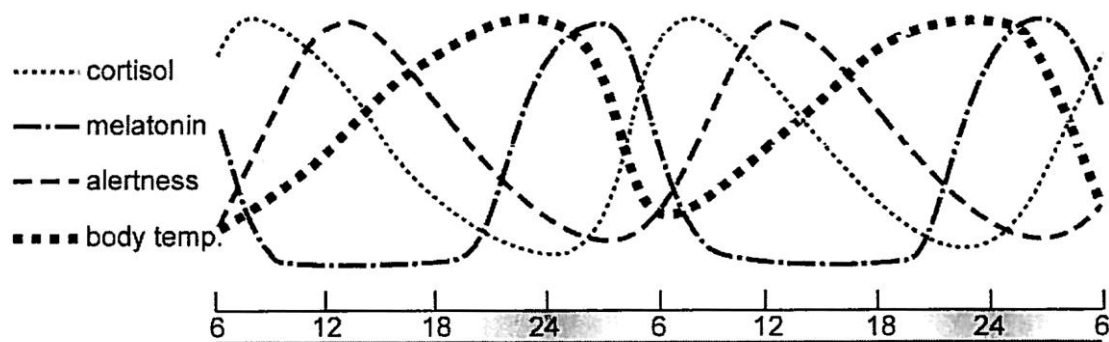


Figure 4.5: Diagrammatic graph of typical phases of various biological functions; melatonin, cortisol and CBT. CIE 158:2004 from Philips Lighting originally

Badia et al (1991) showed in their research that body temperature varies with different intensities of light exposure during night time hours but that it also required the same amount of time to observe a change as with the suppression of melatonin. They summarised therefore that the effect of light on core body temperature could be linked to the level of melatonin present in the body and that melatonin plays a role in regulating body temperature. As this biological response has been shown to be linked to the presence of melatonin within the body it is often used as a secondary marker for the effect of light stimulus on the body (Boivin & Czeisler, 1996) (Cajochen, Zeitzer, Czeisler, & Dijk, 2000).

The sensitivity of body temperature to slight changes in light exposure at night as well as to lower levels of illuminance led Czeisler et al (1989) to suggest that ambient light could be considered as an environmental factor that masks the inherent temperature rhythm along with other factors such as activity level and the consumption of food. This suggests that slight changes in the internal lighting environment could have an impact on core body temperature during the night. More consideration needs to be taken of the exposure to light at night either

to increase wakefulness or promote better sleep by reducing potential exposure. Research has not shown the same impact of light stimulus on core body temperature during the day time hours which may be due to the fact that during the day the endogenous temperature rhythm is at its peak.

4.2.2.4 Subjective alertness

A number of studies have explored the link between exposure to light stimulus and increased subjective alertness (Badia, Myers, Boecker, Culpeper, & Harsh, 1991) (Cajochen, Zeitzer, Czeisler, & Dijk, 2000) (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003). The majority of these studies have focused on the effect of light during night-time hours and the connection between the suppression of melatonin and increased alertness. Like body temperature, alertness has been shown to peak during the daytime when there is very little melatonin present in the body. This relationship is diagrammatically shown in Figure 4.5. It suggests that there is a connection between the level of the hormone melatonin in the body and subjective alertness and that an increase in light stimulus could in turn have an effect on alertness through suppression of melatonin at night.

A connection between light stimulus during the day and an increase in subjective alertness has also been identified by other researchers (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003) (Vandewalle, et al., 2006). These findings are also supported by a number of studies of productivity in the workplace which show possible correlation between daylight, alertness and concentration (Heschong Mahone Group Inc, 2003b). Cajochen et al (2000) show that the characteristics of dose-response functions for subjective alertness are similar to those for melatonin suppression and circadian phase shifting. They note that this may suggest they are mediated by the same receptive elements within the eye and retinohypothalamic pathways that mediate the circadian responses to light. However this does not rule out the possibility that there could be another neural pathway that mediates light information to the part of the brain connected with arousal and alertness.

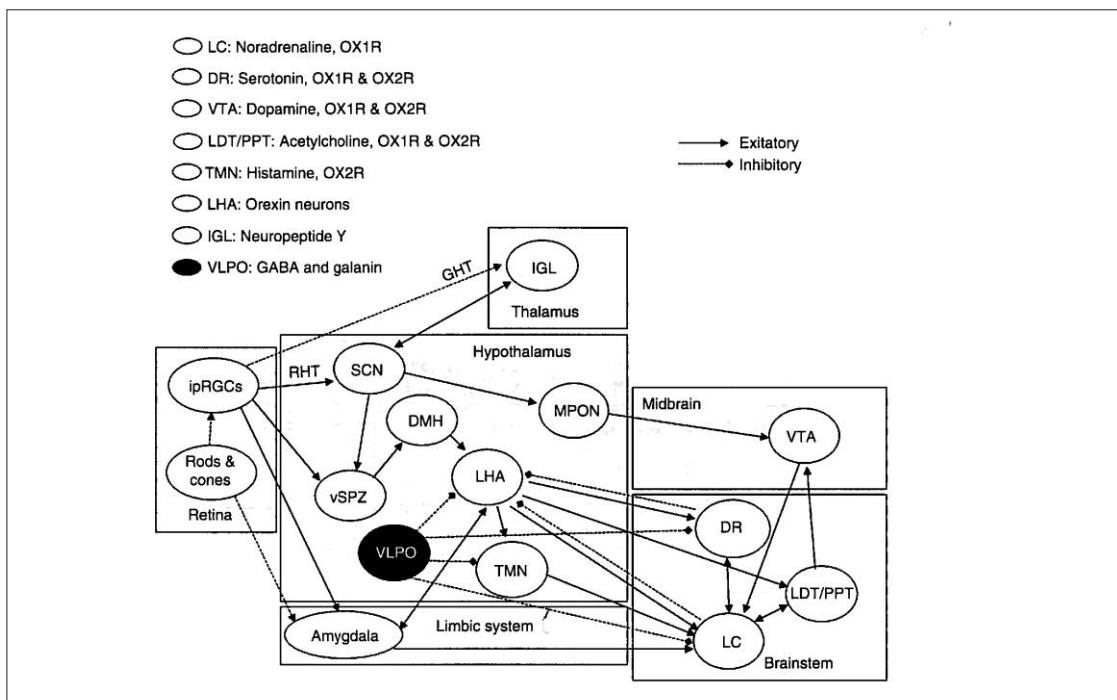


Figure 4.6: Neural connections diagram from Rautkyla et al (2012)

Research by Aston-Jones et al (2001) initially investigated the possible connection between the SCN which receives non-visual light information from the retina and the part of the brain responsible for arousal and the production of cortisol. They suggest that non-visual light information received at the eye is also transmitted to the adrenal gland as described above. This process is described in a diagram presented by Rautkyla et al. (2012) shown in Figure 4.6 where connections between the photoreceptor cells in the retina and different parts of the brain are diagrammatically represented.

The study by Rautkyla et al (2012) proposes that there is also a pathway connecting the retina and the limbic system along which non-visual light information is transmitted in particular to the amygdala and then in turn to the arousal system. This is shown diagrammatically in Figure 4.7. A potential connection between light that is received at the eye and an emotional response might account for the effect of light on daytime alertness. This is the first publication describing such a model but other studies suggest that there may be more than one mechanism involved in the non-visual processes mediated by the human retina (Vandewalle, et al., 2007) (Plitnick, Figueiro, Wood, & Rea, 2010) (Rea, Figueiro, Bierman, & Hamner, 2012). This potential secondary model may be further complicated by the connection to emotion, a key neural process controlled via the limbic system. As Rautkyla suggests the alerting affect of the light stimulus will heavily depend on the emotions induced in the individual, those adding a greater element of subjectivity. This will further complicate a definition of lighting characteristics.

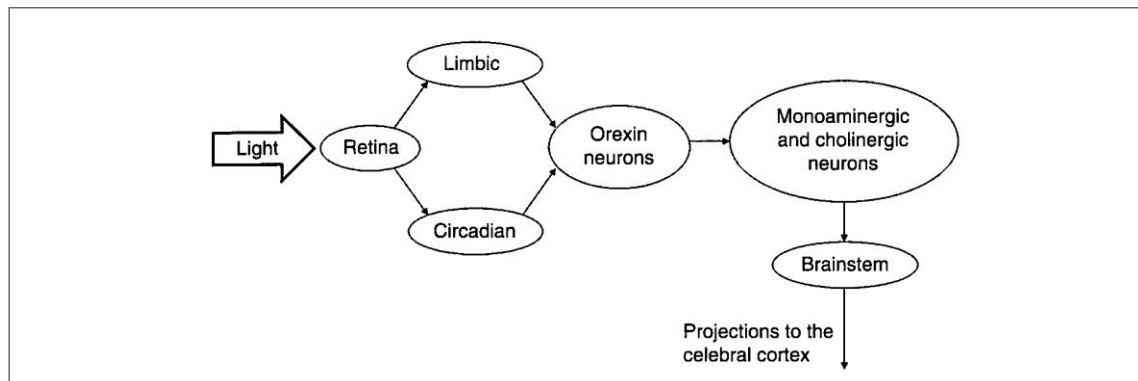


Figure 4.7: Two pathways of light information taken from Rautkylä et al (2012)

It may be concluded that there is a likely connection between the light received at the eye, the emotional response to the surroundings and therefore alertness. Rautkylä et al (2012) suggest that more work is needed to explain how this system works in parallel with the circadian system, explaining the link between light exposure and the enhancement of brain responses and daytime alertness. There are strong indications that there may be other mechanisms through which light information effects alertness, as Provencio (2011) notes many researchers believe that there is still more to understand about the interaction of these physiological systems but until physical studies are undertaken it is not possible to fully understand the impact this might have on the application of lighting design.

4.2.3 Novel light sensitive cells

The inherent differences between the visual and non-visual or non-image forming responses of the human body to light stimuli highlight the need to further understand which part of the eye is responsible for mediating this light information. Biologists have known for a while that many animals have organs that detect light beyond those necessary for image forming. For example changing light conditions may signal to an animal that they could be exposed to a predator or excess solar radiation to which they would then respond by either employing camouflage or moving to avoid the source. As Provencio (2011) notes this requires detection of light but does not necessarily involve vision. Animals also utilise the presence of light to entrain their day/night cycle detected by photosensitive cells not necessarily within the eye. Described in studies by Menaker in the 1970s that showed sparrows entrain their day/night cycle using photosensitive cells in their brains which are triggered by light penetrating their feathers, skin and skull to reach the brain.

Biologists believed for a long time that the rod and cone cells were the only photoreceptive cells in the human retina. It was therefore believed by some that any other photoreception

must occur somewhere else within the body such as when light penetrates the skin. Further investigation into non-visual responses to light with human subjects has proven that extra-ocular photoentrainment does not take place in humans as it does in other animals and that all light induced physiological responses are mediated by the eye (Lockley, et al., 1998). Early research by Keeler in the 1920s showing that some mammals may have photoreceptors within the eye not involved in vision prompted some researchers to investigate whether this was also the case for humans.

Investigations with blind and partially sighted people who still have one or both eyes have shown that circadian entrainment still takes place even though the visual system does not work. The fact that non-visual responses to light must take place within the eye was further emphasised by research with those that have lost both eyeballs (Czeisler, et al., 1995). These subjects were unable to reset their circadian rhythm to the external 24 hour cycle and suffered with a free-flowing rhythm controlled only by the endogenous regulation as described above. This clearly identified that it is not necessarily the same part of the eye that controls the visual system that also controls other non-visual processes.

The human brain is connected directly to the photoreceptor cells within the retina at the back of the eye, essentially an extension of the brain. Initial research has shown (Moore, 1983) (Brainard, et al., 2001b) that the neural pathway that controls circadian regulation by light in humans is the retinohypothalamic tract, connecting the retina to the suprachiasmatic nuclei (SCN). The eye as a collector of light information therefore plays a role not only in the visual system but in other physiological systems. Retinal Ganglion Cells (RGCs) within the surface layer of the retina send light information detected by rods and cones to the visual cortex within the brain via the optic nerve. Research findings from studies with mice indicated that a third photo-sensitive cell may be responsible for entrainment of the circadian system (Freedman, et al., 1999) as well as the suppression of the hormone melatonin (Lucas, Freedman, Muniz, Garcia-Fernandez, & Foster, 1999). These photosensitive cells which detect light independently of the rod and cone cells have since been discovered within the retinal ganglion cell layer of the human retina and send light information directly to the brain.

Most retinal ganglion cells (RGCs) are not sensitive to light but perform a role of transmitting light information from the rod and cone cells to the brain via the optic nerve. Research has shown that there are some retinal ganglion cells, those that contain a photosensitive pigment that are intrinsically light sensitive and relay the light information they detect directly to the SCN via the optic nerve. Rod and cone cells are designed to relay details about individual

points within a specific scene, providing contrast and detail as each cell only responds to light falling on a very small part of the retina. Intrinsically photosensitive RGC cells have been shown to respond to light falling on a much wider area of the retina. Research by Provencio et al (2002) showed that light detecting RGCs have networks of receptive dendrites covering large areas of the retina unlike the rod and cone cells.

These studies into the non-visual response of the eye began to suggest that the characteristics of the necessary light stimulus for these responses could be completely different to those for the well documented visual system of rod and cone cells (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980) (Brainard, et al., 1988). Initial findings suggested that a far greater intensity of light was needed in comparison to that necessary for performance of the visual system. Further investigation into the effect of light stimulus on the non-visual system suggested that parameters such as duration could also exert different effect. This provided strong evidence that a different photoreceptor to the standard rod and cone cells, responsible for the visual system, mediated these non-visual processes such as the circadian system. Although research is ongoing it is agreed that non-visual photoreception is mediated by more complex or novel mechanisms than that of the visual system.

In order to understand more about this novel photoreceptor it was necessary to identify the light sensitive photopigment that it contains. A growing number of studies have been undertaken to understand the exact nature of this novel photoreceptor and the related photopigment. Some studies have identified potential opsin-based photopigments which could be responsible for this non-rod, non-cone response such as vertebrate ancient opsin (Soni & Foster, 1997) and melanopsin (Provencio, Rodriguez, Jiang, Hayes, Moreira, & Rollag, 2000). Other studies have also identified a role for cryptochrome, a retinal vitamin B₂-based photopigment as discussed by Thapan et al (2001). However other investigations have suggested that these opsins and cryptochromes are redundant in mediating light in studies with mice.

By looking at the effect of a range of different light stimuli on a given non-visual process it is possible to understand more about the sensitivities of this neural function therefore the potential absorption spectra of the photopigment that transmits light information. Two of the most commonly cited studies which identified possible action spectra for the novel photopigment were by teams on either side of the Atlantic, Thapan et al (2001) at the University of Surrey, UK and Brainard et al (2001b) at Thomas Jefferson University, Pennsylvania, USA. They were both looking to produce a clear action spectrum for a non-

visual response such as melatonin suppression known to be stimulated by light received at the eye which would tell them more about the photoreceptor involved in this mechanism. Both studies produced very similar results. These action spectra for the suppression of melatonin suggested peak sensitivity of much shorter wavelength than that of either the rod or cone cells. This provided evidence for a novel short wavelength photopigment responsible for light induced suppression of melatonin (Brainard, et al., 2001b) (Thapan, Arendt, & Skene, 2001). It was also suggested that the novel photoreceptor could be a vitamin-A based opsin molecule. Although these studies emphasise the presence of a novel photoreceptor it did not prove conclusive as to the exact identity of the photopigment.

Another research avenue based on the initial discovery of a novel photoreceptor suggests that the photopigment responsible for transducing the non-image system produces a protein called melanopsin which allows it to detect light. Melanopsin is similar to the protein pigment or opsins found in rod and cone cells that enable them to detect light. This protein was named following the discovery that the pigmented cells in the tails of tadpoles, called dermal melanophores, still adapted under light exposure even though removed from the tadpole itself (Provencio, Jiang, De Grip, Hayes, & Rollag, 1998). Research into amphibian camouflage techniques and other non-visual photoreception identified the presence of this protein in skin cells of a number of animals. The similarity to opsins found in rod and cone cells led scientists to investigate whether they existed in other light detecting cells such as the iris, retina and parts of the brain. Melanopsin was discovered in retinal neurons or retinal ganglion cells (RGCs) of mice and further investigation also showed that those RGCs that contained melanopsin connected to the suprachiasmatic nucleus, the part of the brain that controls the body clock. This discovery led researchers to investigate whether this connection was also similar in humans.

This research has identified that there is a novel photoreceptor in the human retina that collects light information and transmits it to the SCN within the brain. These intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) have also been shown to respond to different light characteristics than the rod and cone cells, the photoreceptors responsible for providing information to the visual cortex. It has been suggested by some researchers (Brainard, et al., 2001b) that the rod and cone cells could therefore be irrelevant to some extent to circadian phototransduction. The results of these investigations are by no means conclusive with uncertainty still surrounding the identity of the photopigment connected to this novel ipRGC as well as whether there is any involvement from other photoreceptors in the eye.

4.2.3.1 Single or multiple opsins

As outlined above there is agreement amongst the research community that there is a non-rod, non-cone photoreceptor that has a role in transmitting light information along the retinohypothalamic tract to the SCN within the brain. There is agreement that some RGCs are intrinsically photosensitive and relay light information directly to the brain via the optic nerve, described as ipRGCs. There is some evidence to suggest ipRGC contains the photopigment melanopsin which is known to have a peak sensitivity of around 480nm (Berson, Dunn, & Takao, 2002) (Hattar, Liao, Takao, Berson, & Yau, 2002). From the initial discovery of photosensitive RGCs in the retina there has been uncertainty as to whether melanopsin is the exact photopigment involved. There is also uncertainty whether there is a single or multiple photoreceptors involved in sending non-visual light information to the brain.

Evidence of peak sensitivity and characteristics of this novel photopigment are inconclusive but there are two main schools of thought within the research community; firstly that peak sensitivity is approximately 460nm based on results of the two most commonly cited studies to define the action spectrum for this novel photoreceptor (Brainard, et al., 2001b) (Thapan, Arendt, & Skene, 2001) or that it is a slightly longer wavelength at 480nm based on research findings that suggest melanopsin is the protein pigment involved (Berson, Dunn, & Takao, 2002) (Hattar, Liao, Takao, Berson, & Yau, 2002) (Enezi, Revell, Brown, Wynne, Schlangen, & Lucas, 2011).

Some researchers also still consider that there is some involvement of the rod and cone cells (Rea, Figueiro, Bierman, & Hamner, 2012) based on data from further studies (Belenky, Smeraski, Provencio, Sollars, & Pickard, 2003). Rea et al (2012) argue that the range of spectral sensitivity defined in the empirical data is wider than can be attributed to a single opsin. They argue that the residual errors in both the 460nm and 480nm single opsin models mean that these functions do not fit the data as well as initially suggested. They suggest that neither truly predicted the human circadian response to narrow-band light stimuli when measuring the suppression of melatonin. Their hypothesis is that light across a range of wavelengths might provide optimum stimulus to this novel ipRGC or that a number of photoreceptor cells sensitive to short wavelength light transmit non-visual light information to the brain.

Although this recent publication by Rea et al (2012) highlights the current uncertainty surrounding the identity and peak sensitivity of this novel photopigment, the existence of a third photoreceptor within the human retina which collects and transmits light information to

the SCN is agreed. It is also agreed that this photopigment is sensitive to different characteristics of light than the human visual system. If it is proven that the characteristics of light stimuli necessary to trigger human circadian phototransduction are wholly different to those required for the visual system it will affect the way lighting environments are designed and measured. If the built environment does not provide light to stimulate both the non-visual system as well as the visual system it is possible that these environments will prove detrimental for the physiological well being of the occupants.

4.2.4 Potential health implications

As described above it is now known that the eye plays a role as a photoreceptor for light stimuli connected to many inherent physiological processes. These physiological processes have a knock on effect on the overall health of the person particularly related to the presence of certain hormones within the body. Whether someone receives the right light stimulus to maintain these physiological processes or not may have a significant effect on secondary health implications. The amount of light received by the eye as the collector of this information is dependent to a certain degree on the lifestyle of the person, their job and where they live. Those people that work in an office or any internal environment will spend the majority of their waking hours inside a building reliant on that environment to maintain their well being (Leech, Nelson, Burnett, Aaron, & Raizenne, 2002; Schweizer, et al., 2007). Many of these environments will be wholly supported by artificial means whether that is ventilation or lighting. A number of potential secondary health implications related to internal lighting environments such as SAD, response to shift work and even the symptoms of dementia and Alzheimer's disease highlight the potential effect of lifestyle and the built environment on well being.

4.2.4.1 SAD

Seasonal Affective Disorder (SAD) is a sub-type of depression defined by recurring symptoms related to a specific time of year but not present throughout the rest of the year, most common in the winter months. Summer SAD is also reported by some patients but Winter SAD is more prevalent with a percentage of people also reporting sub-syndromal symptoms of winter SAD. Symptoms range from those typical for other non-seasonal forms of depression such as reduced interest in most activities as well as feelings of depression to atypical symptoms such as increased sleep and increased appetite with winter SAD and decreased sleep and loss of appetite with summer SAD. Research suggests that 5% of the US population

suffer with SAD and a further 10-15% with sub-syndromal symptoms¹ (Wehr & Rosenthal 1989, (Kasper, Rogers, Yancey, Schulz, Skwerer, & Rosenthal, 1989)). Although the exact cause of SAD is as yet unknown, with a reduction in light and the disturbance to the circadian system an unproven explanation, bright light therapy has been shown to be a successful treatment. It has also been suggested that there is a positive correlation between prevalence of SAD and an increase in latitude of a person's home (Rosen, et al., 1990) but this has not been conclusively proven. People living in extreme northerly locations with little or no exposure to natural light in the winter months have been shown to suffer with greater symptoms of depression in some studies (Broadway, Arendt, & Folkard, 1987) but the reduction in light exposure has not been demonstrated as the sole cause of SAD.

Almost 20 years ago an investigation into Seasonal Affective Disorder (SAD) and its treatment with bright light therapy was pioneered by the National Institute of Mental Health in the USA. Light therapy has been proven to work in a large number of cases of SAD, when patients are exposed to bright light which can range from 2500lux to 10,000lux, duration of dose dependent on illuminance ranging from 2h to 30mins respectively. Treatment is normally administered from a light box with light provided by artificial lamps such as fluorescents as it has been noted by Boyce (2003) that the spectral distribution of the light source is not relevant at such high illuminances. The timing of light therapy is proposed by some to be more effective during the morning (Terman, Terman, Lo, & Cooper, 2001) which suggests that it is connected to the phase advance of the circadian system, discussed in more detail below. The study by Terman et al (2001) indicated that there was a more potent effect of bright light therapy (10,000lux for 30mins) when administered in the morning using the onset of melatonin suppression as a marker. However it is unclear whether the increased potency of morning light is due to the phase-shifting of the circadian system and whether this fully defines a positive improvement in the symptoms of SAD. Others suggest that timing of exposure is not that important (Wirz-Justice 1993).

A positive response to treatment is generally seen within 3 days to one week with atypical symptoms such as increased sleep and appetite showing a more immediate improvement. Light therapy is not a cure for SAD as if treatment is stopped symptoms tends to return, it has also been shown by some not to be an effective treatment on its own particularly with typical

¹ Sub-syndromal defines symptoms that fall short of the symptoms for a defined illness or disease such as depression or seasonal affective disorder. People within this category might be described as having mild symptoms.

symptoms of depression (Pjerk, Winkler, Statny, Konstantinidis, Heiden, & Siegfried, 2004). Some side effects have been reported as a result of exposure to high illuminances of artificial light such as headaches and mild disturbances to vision but not such that would prevent treatment unless the patient is susceptible to retinal damage. Although exposure to bright light in the morning may not be a suitable treatment for all those that suffer with SAD due to photosensitivity or hypersomnia² which prevents them being awake at the necessary time for light treatment, the research does suggest that receiving high illuminance levels during the morning hours supports well being. This could have a potential impact on the design of spaces that people inhabit at this time of day, most likely their own home. The increased use of so-called SAD lamps has shown that many people are keen to improve the lighting environment within their own home in the hope of improving symptoms.

4.2.4.2 Shift work and the potential Cancer risk

People that have jobs which require them to work during the night on a regular basis such as doctors and nurses expose themselves to light at a time of darkness when their internal body clock would naturally be in a phase of sleep. In order to maintain a safe working environment and perform tasks required of them the environment is lit with artificial light. This light is often at high illuminances to support visual performance but also to a certain extent to combat drowsiness and fatigue and prevent potential accidents. The dose response of the circadian system has temporal nature, such that it is sensitive to light at certain times. Receiving light stimulus at times when it is not naturally expected can therefore alter the individual's inherent circadian rhythms. The most immediate effect is on sleep patterns but with a potential impact on other physiological processes there could be latent effects on other health outcomes.

A link between light at night (LAN) and an increased risk of breast cancer was suggested by Stevens & Rea (2000) in connection to the suppressive effects of light on the hormone melatonin. The changes to both timing and quantity of hormones released into the body could potentially have implications on the way it behaves in relation to other processes such as cell regeneration and absorption of nutrients or fats. Stevens & Rea suggest that these environmental changes could also have an impact on the prevalence of certain hormone related cancers such as breast cancer. In connection to this it has also been shown that women may be more sensitive to light at night than men (Monteleone, Esposito, La Rocca, & Maj, 1995).

² Hypersomnia describes a condition in which the sufferer sleeps for excessive periods of time often finding it difficult to awake in the morning.

Other studies have shown that there are less incidences of cancer in blind people especially breast cancer which some believe supports the hypothesis that there is a connection with melatonin suppression by light received at the eye (Dauchy, Blask, Sauer, Brainard, & Krause, 1999). In a study into the connection between the absorption of fatty acids, changes in metabolism and tumour growth Dauchy et al (1999) showed a connection between very low levels of light at night and increased tumour growth. Tumour growth rates were 2-3 times greater in the groups exposed to dim light during the dark phase and those exposed to constant light than those in the group exposed to a normal 12 hour light:dark cycle. They noted that this showed dim light had a similar potency to constant light exposure in the growth of tumours, suggesting that even a small amount of light at night could have an impact on the development of cancer.

The dim light level used within the above study was not sufficient to alter the circadian rhythm of food intake, something that was evident in the constant light group but it did have an effect on the suppression of melatonin. This indicates that a light level necessary to change more patent circadian rhythms such as food intake is not necessary to have an effect on tumour growth. Therefore it may not be as obvious that a person is being exposed to a potentially harmful amount of light.

Although research is ongoing in this area the suggestion that exposure to light at night might increase the incidences of breast cancer in women highlights the significance of light received at the eye for non-visual processes. It indicates that both the timing of exposure and intensity of light need to be taken into consideration in order to create lighting environments that support human well being. In terms of those people that are involved in shift work, exposure to light at night may be more difficult to avoid particularly with an ever increasing 24/7 workforce. More needs to be known about the importance of an individual's light history on their long term well being, such that limits may be put in place for the period of time a person is able to work during the night exposed to high levels of artificial light.

4.2.4.3 Alzheimer's disease

As with the treatment for Seasonal Affective Disorder (SAD) recent studies have started to indicate that the treatment of people with Alzheimer's disease (AD) could be improved with light therapy (van Someren, et al., 1996). Patients with AD often have disrupted patterns of sleep and activity, reduced cognitive behaviour and increased agitation and anxiety. They are quite often out of sync with the world around them waking in the middle of the night and napping regularly in the middle of the day. This daily pattern could be worsened by a reduced

amount of light being received at the retina. As the body ages the eye also ages like other organs, the lens deteriorates thickening and developing pigmentation that alters the transmission of light particularly at the shorter end of the visible spectrum. A study by Lerman (1987) showed an initial reduction in overall light transmittance between approx. 25 and 54 yrs of age followed by a further reduction between 54 and 82yrs of age. As shown in Figure 4.8 at 82yrs of age the study showed approximate transmittance of 30-35% above 500nm wavelengths and 15-30% at wavelengths between 450-500nm. A reduced amount of light is received at the retina and in turn by the brain both for visual performance as well as for other non-visual process such as circadian phase resetting and the suppression of melatonin.

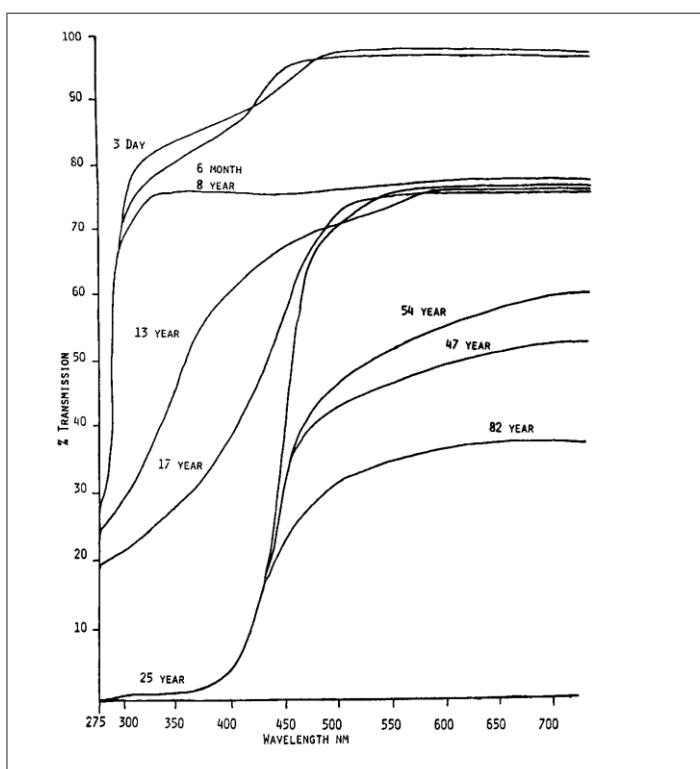


Figure 4.8: Graph showing the transmission characteristics of the normal ageing lens (taken from (Lerman, 1987))

This reduction in light information in turn means that the brain is less active in sending signals to the rest of the body. As described earlier many bodily systems are controlled by the hypothalamus or body clock therefore as it becomes less active day to day activities become more difficult and regular bodily rhythms are disrupted. Studies undertaken by Dr. Eus Van Someren at the Netherlands Institute of Neuroscience (van Someren, et al., 1996) (Riemersma-van der Lek, Swaab, Twisk, Hol, Hoogendijk, & van Someren, 2008; Van Someren, Kessler, Mirmiran, & Swaab, 1997) have shown that increasing the amount of light that is received at the eye improves the messages that are sent to the brain. As the body clock becomes

synchronised with the surroundings once again patients show improvement in their symptoms with improved sleep patterns, increased cognitive behaviour and reduced agitation. One study recorded hourly activity data of dementia patients in an elderly care centre, some of which had AD, before, during and after bright light therapy was administered over a 5 day period (Van Someren, Kessler, Mirmiran, & Swaab, 1997). The results clearly showed that during the period of light therapy there was a significant decrease in the amount of activity during the subjective night-time than before or afterwards, shown in Figure 4.9. These results are said to match results achieved through administering drugs but have the additional benefit of no adverse side effects such as nausea. Light therapy has also shown the positive benefit of subjective improved mood across the patients observed. This research could have a significant impact on the lighting design of spaces within elderly care centres not just to benefit those with Alzheimer's disease but all those residents that have a deterioration of the eye which reduces the amount of light information reaching their brain and in turn affects their sleep/wake cycle.

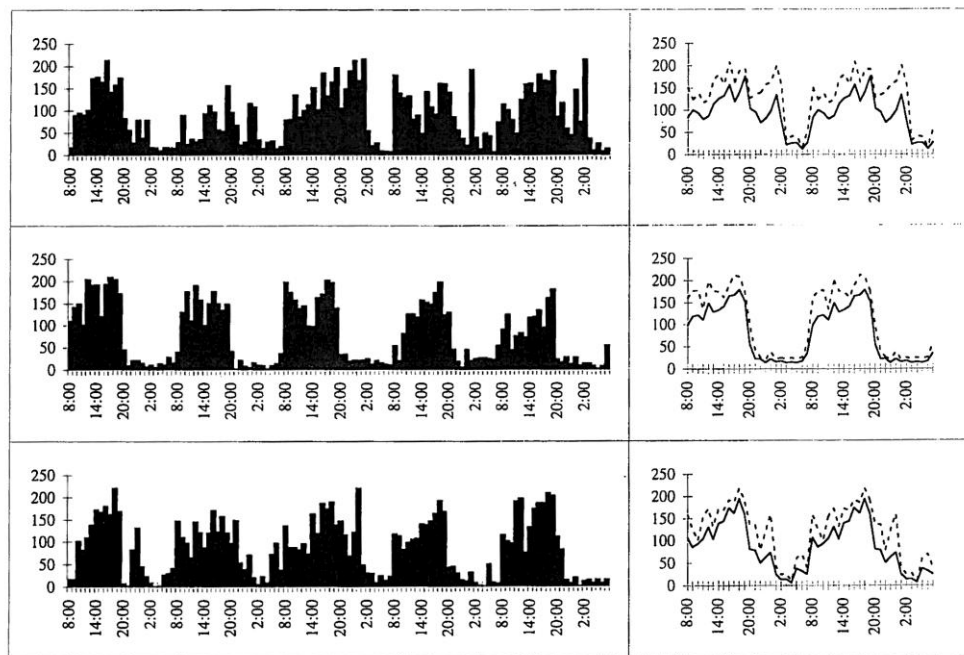


Figure 4.9: Hourly activity data of a patient with AD over 5 days, before, during and after bright light treatment (after (Van Someren, Kessler, Mirmiran, & Swaab, 1997))

Another factor related to the care of Alzheimer's patients or those with dementia is the need for regular observations. It is often the case that during the night a carer will need a certain level of illumination in order to undertake periodic checks but in doing so interrupts the sleep of the person. The light received by the person during their sleep can result in a disruption to

their sleeping pattern which is in turn observed in an increased lethargy during the day which can cause agitation and confusion. Research by Figueiro & Rea (2005) into the use of amber LEDs within elderly care facilities and nursing homes has been shown to reduce disruption to sleep during night time observations. An example of the lamps installed is shown in Figure 4.10. Although these lamps provide illuminance levels so that necessary visual tasks can be performed by the carer the wavelength of the light provided does not appear to disrupt the sleep pattern of the person they are looking after. Based on the emerging evidence that the circadian system is sensitive to a shorter wavelength light these lamps produce light at a longer wavelength of an amber colour. They have been trialled both as bedside/observation lights but also to illuminate doorways to bathrooms and around the edge of handrails to aid use of the bathroom during the night.



Figure 4.10: Trial observation rooms using amber LEDs around the bed and bathroom doorways (Figueiro & Rea, 2005)

This research highlights the differences between the performance characteristics of the human visual system and the non-visual system. It shows that certain illuminance and wavelengths of light provide a lighting environment suitable for some visual tasks whilst not delivering the necessary light information to stimulate the non-visual system. If further research into this area shows that these responses are common to all people it could alter the lighting environments provided for a range of different scenarios and activities related to performing tasks at night and promoting sleep.

4.2.5 Section summary

Research outlined above has identified that there are a number of physiological processes within the human body that also respond to light as an external trigger such as circadian

rhythms including core body temperature, sleep/wake cycle and the regulation of hormones. The indications of research by the biomedicine, neuroscience and chronobiology communities suggested that the characteristics of light to stimulate the non-visual system are different to those required by the visual system.

Empirical studies have identified the existence of a third novel photoreceptor in the human retina beyond the rod and cone cells. This intrinsically photoreceptive Retinal Ganglion Cell (ipRGC) unlike the rod and cone cells both collects and transmits light. This information is transmitted via the retinohypothalamic tract to the brain and specifically to the suprachiasmatic nuclei (SCN) within the hypothalamus which acts as the body's internal clock. Although the exact identity of the photopigment responsible for this phototransduction is as yet undefined there is agreement amongst the research community that the dose response is different to the familiar rod and cone cells in reference to light intensity, the specific wavelength as well as the timing and the duration that is received.

The system of photometry defined by the sensitivities of the rod and cone cells is well established. The fact that this non-visual response to light may require different stimulus throws into question whether the lighting environments most people currently inhabit are suitable. The growth of evidence underlining the possible secondary health implications of the lighting environment also underlines that without this deeper understanding there may be long term implications. Research outlined above suggests that these secondary implications affect those people that have desynchronised circadian systems due to lifestyle or other health related issues. However as a large percentage of the population of the developed world spend the majority of their waking hours within a building through work or other aspects of their lives the lighting environment within these spaces could play an important role in their well being. The ability to provide lighting environments for well being as well as visual performance has been suggested by some to offer the opportunity to optimise the use of light in all architectural applications but more specifically therapeutic environments.

Although the evidence is not yet definitive, based on this growing body of research a more detailed evaluation is necessary to begin to identify a set of parameters for light stimulus to support these non-visual responses to light. It is necessary for designers to begin to understand the potential differences between the visual and non-visual system mediated by the eye and the implications they might have for the design of internal spaces and more specifically the lighting environment.

4.3 The parameters for stimulants of the eye

As research is ongoing care should be taken when considering the non-visual requirements of a lighting environment. However based on the research communities agreement that light is the main external trigger for other physiological processes and that a novel third photoreceptor within the eye is involved in mediating this light information it would be reasonable to adopt a precautionary approach such that the necessary stimulation characteristics for the non-visual system are explored. Ultimately it is important that the characteristics of the light required for these non-visual processes are incorporated into the design of lighting environments. However until there is international agreement over the specific dose response of these physiological processes and the required lighting characteristics to stimulate a response any consideration within the lighting environment will have to be based on assumptions formulated from the current empirical evidence. A few research teams have acknowledged that a new set of parameters need to be defined, a new system of 'circadian photobiology' based on the sensitivities of these non-visual processes (Brainard, et al., 1988; Rea, 2002a; Anderson, Mardaljevic, & Lockley, 2012). Whilst suggestions have been made as to the range of sensitivities of the non-visual system these researchers have been clear to note that as further empirical data becomes available and more detail is known about this system their models may have to be refined.

As explorative research to define the sensitivities of the novel photoreceptor has shown there are certain key differences in comparison to the rod and cone cells. For example, the spectral sensitivity (Freedman, et al., 1999; Provencio, Rodriguez, Jiang, Hayes, Moreira, & Rollag, 2000; Brainard, et al., 2001b; Thapan, Arendt, & Skene, 2001; Enezi, Revell, Brown, Wynne, Schlangen, & Lucas, 2011) the quantity or intensity of light (Boivin & Czeisler, 1996; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000) as well as the timing and duration of exposure (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997; Wehr, Aeschbach, & Duncan Jr, 2001). This section will look in more detail at the stimulation characteristics of the non-visual physiological processes based on continuing research to ascertain potential threshold ranges. This is heavily centred on performance factors for lighting such as light intensity or illuminance, the wavelength sensitivity and therefore spectral distribution of the light source as well as the timing and duration of light exposure.

Entrainment of the circadian system is often the focus of investigations into the effect of light on non-visual physiological processes based on evidence of the connection between the eye and the suprachiasmatic nuclei as discussed above. Some researchers such as Rea et al (2012)

argue that it is not clear whether all non-visual responses to light, even those entrained within a circadian rhythm, rely on the same stimulation characteristics. Through evaluation of empirical findings from the biomedical and neuroscience communities the following section will outline the characteristics of a few of these physiological processes defined through the performance factors stated above; the regulation of the hormone melatonin, circadian phase-shifting and subjective alertness and identify the potential similarities and differences between them. This will provide a basis from which to analyse whether the lighting environments within modern buildings provide the necessary light stimuli to support these other processes.

4.3.1 Wavelength

One of the initial identifying factors for the novel photoreceptor was that it had peak sensitivity to a wavelength of light different to that for either the photopic (cones) or scotopic (rod) systems (Berson, Dunn, & Takao, 2002; Provencio, Rodriguez, Jiang, Hayes, Moreira, & Rollag, 2000). As outlined in Chapter 2 rods and cone cells have different absorption spectra, which describe their sensitivity to particular wavelengths of light, the wavelengths of light to which they most readily respond. This difference allows them to perform different roles within the processing of visual information. The clearest distinction of the difference between the classic rod and cone cells of the visual system and the novel photoreceptor is the spectral sensitivity, in order to properly indentify the novel photoreceptor its peak sensitivity had to be established. Based on the research findings this section will look to define what is known about the spectral quality of light needed to stimulate non-visual physiological processes mediated by the eye.

4.3.1.1 Melatonin suppression

As described above the regulation of melatonin is entrained by a circadian rhythm with its peak during the subjective night-time and therefore highest melatonin levels. This is the time that light stimuli has the most potent effect on the melatonin levels within the body, it therefore provides the clearest picture of the sensitivities of this non-visual process to light exposure. The suppression of melatonin has been commonly used as an indicator of the effect of light stimuli throughout studies to explore the response of the novel photoreceptor and the neural pathways between the eye and the brain.

Early studies suggested that high intensity broad spectrum bright white light with energy produced across the visible spectrum would be sufficient to suppress of the presence of the hormone melatonin to daytime levels (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980).

However further research highlighted the increased potency that the shorter wavelengths had on certain non-visual processes such as the suppression of melatonin (Munch, Kriebitzsch, Steiner, Oelhafen, Wirz-Justice, & Cajochen, 2006). In particular the investigations showed a spectral sensitivity to light at the blue end of the spectrum. This is different to the photopic system, based on the response of the cone cells, with peak sensitivity at the middle of the spectrum at around 555nm, a yellow-green light (Figueiro, Eggleston, & Rea, 2002).

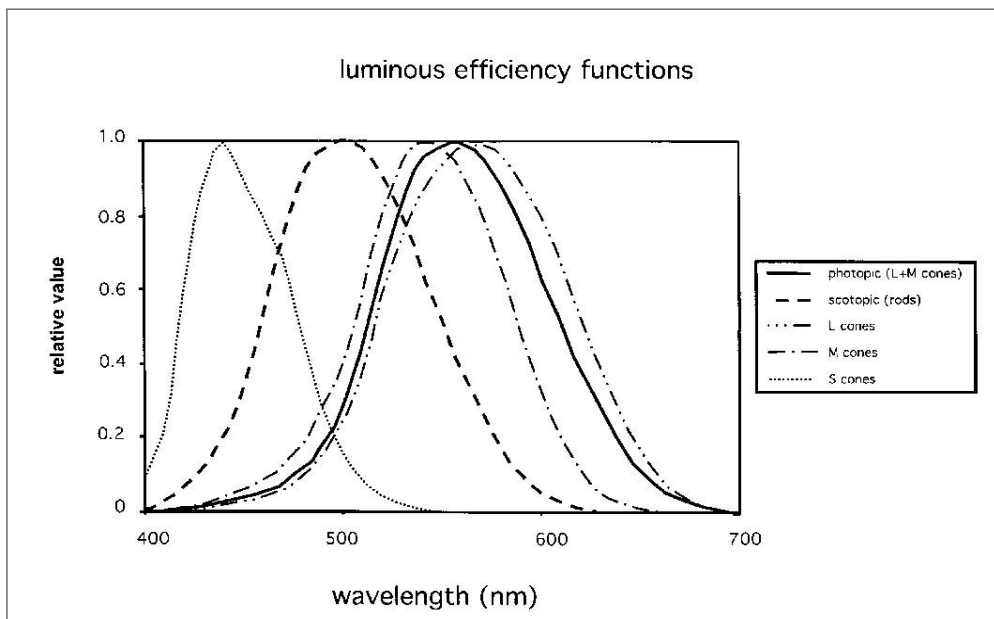


Figure 4.11: Luminous efficiency function for photopic and scotopic as well as individual L, M and S cones (Stevens & Rea, 2000)

Some studies have suggested that there is potential for the scotopic system (rod-based) to be involved with mediating light information to trigger the suppression of melatonin with peak sensitivity at a shorter wavelength of 507nm (Rea, Bullough, & Figueiro, 2001; Altimus, et al., 2010). However, even though the results of the investigation showed that light at this shorter wavelength was more effective at suppressing melatonin production, it did not provide conclusive evidence. It still left the possibility that inputs from all photoreceptors are combined to control melatonin levels therefore light across the spectral range could elicit an affect. Rea et al suggested that this dual response would be similar to pupillary reflex which is dominated by the response of the rod cells but contributed to by input from the cone cells. The findings of these investigations were by no means conclusive with the absorption spectrum for neither of these photoreceptors a direct match for the action spectrum for melatonin suppression. This suggests that they cannot solely describe the phototransduction of the circadian system. They concluded that the non-visual photoreception was likely to be

mediated by more complex or novel mechanisms with a spectral sensitivity similar to that of the scotopic system, whether there was multiple photoreceptor input or not.

As outlined above distinguishing the peak sensitivity or the wavelength of light that acquires the greatest response helps to pin point the identity of a given photoreceptor cell. Most photosensitive cells respond to a varying degree across a range of wavelengths of light which defines an action spectrum for that cell. Action spectra are determined by evaluating the amount of photons or energy required for the same biological outcome from different wavelengths of light. The data can then be used to construct an action spectrum from IRC (irradiance response curves) or fluence-response curves at multiple wavelengths based on the response of the photosensitive process being used as an indicator. If the action spectrum is accurately identified it would then be possible to define the input necessary to trigger the same response in future and in turn would identify the relative effectiveness of photons at different wavelengths. This would make it possible to identify the specific photopigment involved in this physiological response and how it is different to other cells such as the rods and cones.

As described earlier two research teams provided findings that suggested peak sensitivity of this novel receptor (Brainard, et al., 2001b; Thapan, Arendt, & Skene, 2001). Monochromatic light at different irradiances were used to test the response of a group of human subjects and the extent to which night-time melatonin levels were suppressed across of range of wavelengths. Both these studies identified very similar potential action spectra for the suppression of melatonin secretion by exposure to light at night and are often cited as providing unequivocal evidence for a novel photoreceptor in the eye as shown in Figure 4.12.

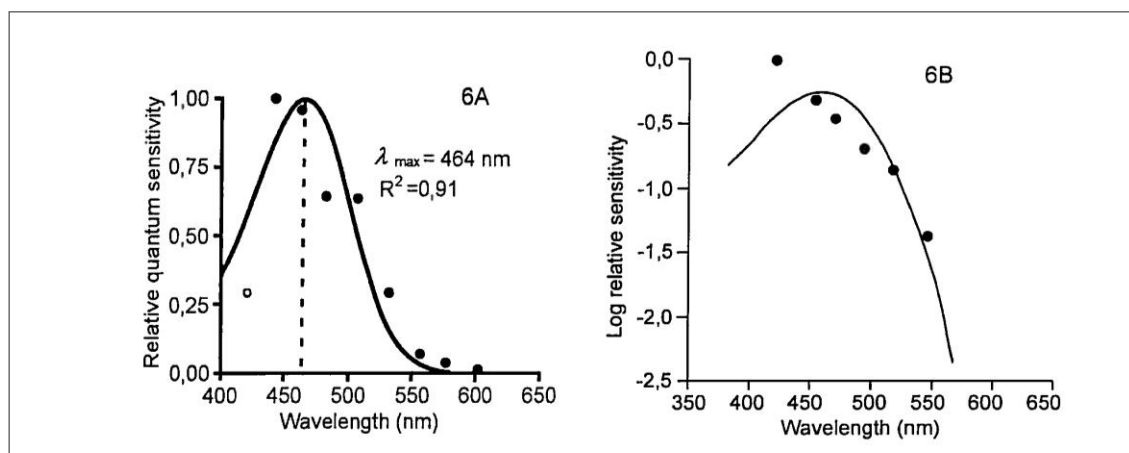


Figure 4.12: Two proposed action spectra for melatonin suppression from study results from (Brainard, et al., 2001b) and (Thapan, Arendt, & Skene, 2001)

By comparing the absorption spectra for the different cone cells as well as rod cells both studies demonstrated evidence for a novel photoreceptor in the eye. As described earlier the human retina has one type of rod photoreceptor with peak sensitivity of 507nm and three types of cone photoreceptors, S, M, and L with peak sensitivities of 440nm, 540nm and 565nm respectively. Following this comparison Thapan (2001) noted that the action spectrum derived from physiological tests was significantly different therefore the photopic or scotopic systems (using the rod and cone cells) could not be the major photoreceptors involved in the suppression of melatonin. This emphasised that image forming and non-image forming photoreception processes in humans could be different and distinct from each other.

Thapan et al (2001) showed that the suppression of melatonin response was most affected by a range of wavelengths between 457-462nm with peak sensitivity occurring at 459nm. This study has narrowed the peak spectral sensitivity to a small range of short wavelength light towards the blue-end of the visible spectrum. The researchers' suggest that these findings emphasise the likelihood that the photopigment is a vitamin A-based opsin molecule. Brainard et al (2001b) established an action spectrum for light-induced melatonin suppression, the results suggesting that a slightly larger range of wavelengths between 446-477nm were the most potent. They propose that a range of wavelengths rather than one specific wavelength are most potent for the stimulation of the circadian system and the pineal gland. This opens up the possibility that there isn't a single photopigment but multiple photopigments involved in transmitting non-visual light information to the brain.

From these empirical studies a number of 'circadian' efficiency functions have been derived to sit alongside the photopic and scotopic functions which show an assumed peak sensitivity of approximately 460nm, as shown in Figure 4.13 below. Although only Thapan et al (2001) recorded a value for peak sensitivity for the suppression of melatonin, 460nm has been assumed by many as the most potent wavelength for this circadian response and in turn the spectral signature of the photopigment involved.

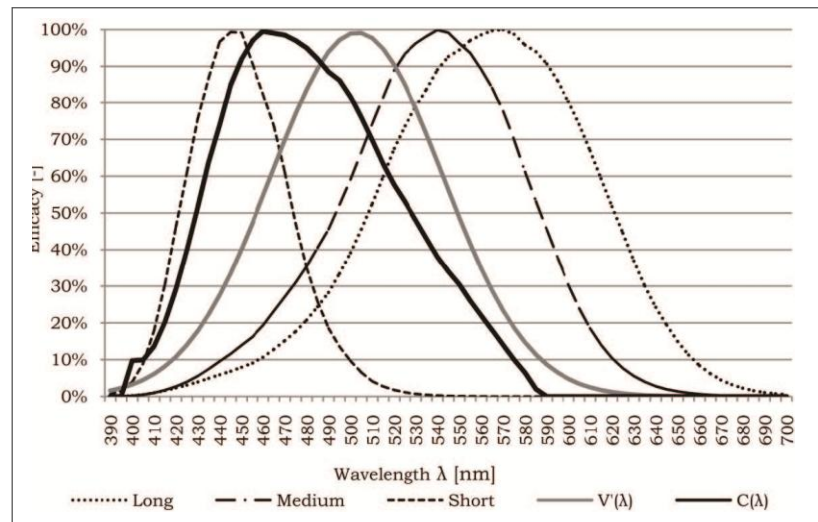


Figure 4.13: 'Circadian' efficiency function overlaid on the photopic and scotopic efficiency functions as derived by Philips Lighting based on data from (Brainard, et al., 2001b) (Thapan, Arendt, & Skene, 2001)

Another school of thought is based on more specific investigations into the physiology of the retina and the novel photopigment involved in non-visual phototransduction. It has been suggested more specifically that the opsin molecule present within the light detecting RGCs is a protein based pigment called melanopsin. This idea is based on research that initially identified the potential presence of a third novel photoreceptor in the mammalian retina (Provencio, Rodriguez, Jiang, Hayes, Moreira, & Rollag, 2000) (Berson, Dunn, & Takao, 2002). A number of separate teams working in the same area identified the presence of melanopsin in retinal ganglion cells (Hattar, Liao, Takao, Berson, & Yau, 2002) and identified an action spectrum for these cells with peak sensitivity at 484nm (Berson, Dunn, & Takao, 2002). Although these initial studies were undertaken with rodents it is thought that there is potential for these cell characteristics to be present within the human retina.

A study by Enezi et al (2011) looking to define a 'melanopic' spectral efficiency function suggested that there was evidence that the response of this novel ipRGC was influenced by light at other wavelengths either directly or via the rod and cone cells. This increases the complexity of the response of this novel receptor to light exposure. Enezi et al showed that it was still possible to define the response of this ipRGC using a spectral efficiency function with peak sensitivity approx. 480nm and that this was more reliable in predicting the response to broad spectrum light than other previously defined methods. This work has been further developed by Lucas et al (2014) in a study which brings together eleven different research departments from across the world to further develop the understanding of the neurophysiological connections between the eye and the brain. Their research emphasises the

peak sensitivity of 480nm based on the melanopsin identity of the photopigment with the ipRGC. Lucas et al conclude however that this photopigment could be inherently bistable, that it has two stable responses such that light of other wavelengths could influence the response of this photoreceptor. They note that it is not yet known whether this bistability has a significant biological effect on the response of this photopigment in humans but studies with other species has shown that it does not significantly affect spectral sensitivity to light exposure. Lucas et al conclude that the response of the ipRGCs could be influenced by light input from all five photopigments; melanopsin within ipRGC themselves as well as the traditional rod and three cone cells as shown in Figure 4.14.

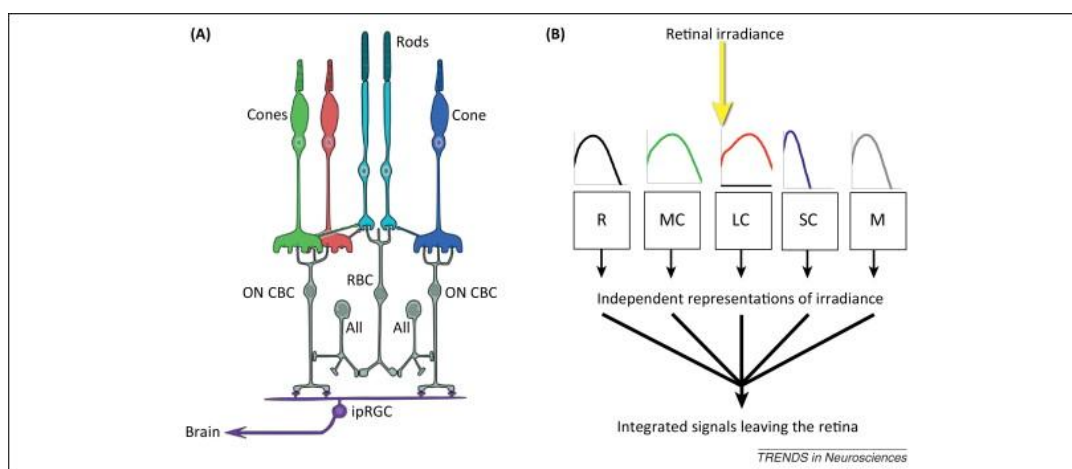


Figure 4.14: Schematic of the retinal circuitry in humans showing the different photoreceptive cells taken from Lucas et al (2014)

Results from these investigations have shown that the primary photoreceptor to stimulate the regulation of the hormone melatonin is different to those involved in the visual system. Short wavelength sensitivity makes it distinct from the classical scotopic and photopic visual systems. In lieu of conclusive evidence of the exact spectral sensitivity of the ipRGCs involved in non-visual phototransduction a number of 'circadian' efficiency functions have been proposed for precautionary application within lighting industry. The initial efficiency function being based on the findings from both Brainard (2001b) and Thapan (2001) studies defined as $C(\lambda)$. This efficiency function has in turn formed the basis of other applied research into a potential framework for a new circadian photobiology (Gall & Bieske, 2004; Bierman, Klein, & Rea, 2005; Pechacek, Anderson, & Lockley, 2008; Anderson, Mardaljevic, & Lockley, 2012). A further 'melanopic' efficiency function $V^2(\lambda)$ has been developed based on the spectral sensitivity of the protein melanopsin proposed as the photopigment within the ipRGCs (Enezi, Revell, Brown, Wynne, Schlangen, & Lucas, 2011) (Lucas, et al., 2014).

4.3.1.2 Circadian phase-shifting

There are a number of physiological processes within the body which have endogenous 24hr or circadian cycles with different peaks and troughs which are controlled from within the hypothalamus as described by the graphic in Figure 4.5. It is not clear whether these different physiological processes have exactly the same stimulation characteristics but research has been undertaken to explore the ability of light to alter the phasing of the inherent circadian system within humans. Anatomical studies have suggested that there is a common neural pathway from photosensitive RGCs to the SCN via the retino-hypothalamic tract (RHT) (Klein & Moore, 1979). Findings from research outlined earlier indicating that blind and partially sighted people are still able to entrain their sleep/wake cycle to the local day/night cycle have further emphasised this connection between light received at the eye and circadian phase entrainment. Establishing whether the response of the circadian phase-shifting is spectrally sensitive, such that certain wavelengths of light are more potent than others and whether this is similar to the response of melatonin regulation will provide a better picture as to the connection between the ipRGCs and the neural pathway to the brain. This will in turn have an impact on the type of light provided by the buildings people inhabit throughout the circadian phase.

A few studies have been undertaken to investigate the direct effect of the wavelength of light on phase-shifting the circadian system, one identifying light at a wavelength of 497nm as having the most effect on phase shifting (Wright & Lack, 2001). This study did not include wavelengths shorter than 470nm and following evidence from other studies that showed melatonin suppression to be most effective with shorter wavelengths around 460nm it would suggest that this study may not have been exhaustive enough. Findings from another study by Warman et al (2003) looked to compare the effect of short wavelength light and bright white light. This showed that low intensity short wavelength light was as effective as high intensity or bright white light. The short wavelength light stimulus used had a transmission spectrum with two peaks at 436nm and 456nm in line with the previous evidence of the sensitivity of melatonin suppression. Warman et al (2003) concluded that the circadian system is generally sensitive to the phase-shifting effects of short wavelength light, which supports other research that suggests that the visual photopic system is not significantly involved.

Evidence for a common neural pathway that conveys light information for a number of circadian responses is supported further by research undertaken to compare the sensitivities of different responses to varying light intensity (Zeitzer, Dijk, Kronauer, Brown, & Czeisler,

2000; Lockley, Brainard, & Czeisler, 2003). Although the study focussed on the dose-response relationship to administered light with saturation thresholds for melatonin suppression and phase resetting being slightly different, the findings also showed that both circadian responses followed a similar illuminance or dose-response curve. Zeitzer et al (2000) noted that this suggests that both light-induced responses are regulated by a common neural pathway providing light stimulus to SCN or human body clock. As the main physiological indicator for the effect of light on the human circadian system is the regulation of the hormone melatonin there are few studies that look to identify the phase-shifting response independently of this physiological outcome. This is most significantly the case when looking to indentify the spectral sensitivity. It has therefore been assumed that the spectral sensitivity of the human circadian system is described by the response of the regulation of melatonin. This therefore assumes that short wavelength light between 460-480nm is most potent to the circadian phase-shifting.

There is also a school of thought that the rod and cone cells may also have some involvement in photo-transduction of non-visual information to the brain (Rea, Bullough, & Figueiro, 2001; Rea, Figueiro, Bullough, & Bierman, 2005; Altimus, et al., 2010). Rea et al (2012) suggest in a more recent evaluation of the research that although there have been a number of attempts to model the spectral sensitivity of the ipRGC linked to the human circadian system none fit the empirical data well. They acknowledge the research proposing a peak sensitivity of 480nm but suggest that it doesn't appear to be conclusive that a single opsin model is the answer. This review by Rea et al (2012) points to the possible involvement of multiple photopigments, suggesting that it's not possible at this stage to rule out a role for the rod and cone cells. This is in line with the findings from Altimus et al (2010) based on studies with mice that suggest that there is a significant contribution from rod cells to the photoentrainment of the circadian system. They suggest that due to the sensitivities of different wavelengths the rod cells in particular work with the ipRGCs to transmit a consistent light signal to the brain suggesting that the circadian system does respond to light at a slightly longer wavelength. The study did suggest that this response is very much dependent on the intensity of the light stimulus. This highlights the need to consider the dose response based on all the stimulation characteristics simultaneously.

4.3.1.3 Subjective alertness

As well as the effect on neurophysiological responses such as hormone regulation, light stimulation has been shown to have an effect on behavioural responses such as alertness

(Badia, Myers, Boecker, Culpeper, & Harsh, 1991) whether this is related to the circadian cycle or whether it has a direct response to stimulation. There is still uncertainty as to whether there is a connection between the neural pathways that transmit light information from the retina to the SCN and other parts of the brain and the adrenal gland but influences on other physiological behaviour through exposure to light have been observed.

A recent evaluation by Rautkylä (2012) suggested a link between the circadian and limbic pathways such that light information also travels to the amygdala and then onto the arousal system. This study acknowledges research evidence by others that the circadian neural pathway and the suppression of melatonin could be linked to subjective alertness. Rautkylä also proposes that there is a second pathway (limbic pathway) also relying on light information being collected by the same ipRGCs as in the circadian pathway. This is partly based on evidence identifying that shorter wavelength light has a stronger effect on emotional responses than longer wavelength light (Vandewalle et al, 2010). This theory is also supported by evidence from another study by Vandewalle et al (2007) in which it was observed that light can influence emotional response via the amygdala. If the same novel photoreceptor connected to the circadian system also transmits light information to the amygdala it would suggest that the spectral sensitivity of this behavioural response is also the same with short wavelength light being most potent.

Two similar studies (Plitnick, Figueiro, Wood, & Rea, 2010; Figueiro, Bierman, Plitnick, & Rea, 2009) looking to establish the effect of long wavelength red light and short wavelength blue light on alertness at night suggest that more than one mechanism could be involved in subjective alertness by light stimulation. Both these studies administered two illuminance levels (40lux and 10lux at the eye) of red (630nm) and blue (470nm) light during night-time hours and measured the levels of alertness via EEG and ECG measurements, self-reported mood and sleepiness as well saliva melatonin levels. The results showed that both red and blue light of the higher illuminance level increased measured levels of alertness in comparison to the dim light environment (1lux). Plitnick et al (2010) also reported that both light stimuli, the long wavelength red light and the short wavelength blue light, resulted in improved mood and a reduction in sleepiness. These studies agree with previous findings that light stimulation mediated by the circadian neural pathway can affect alertness at night but it also shows that alertness can be affected by light without stimulating a circadian response such as the suppression of melatonin.

4.3.1.4 Conclusions for wavelength

Investigations in this area are ongoing with no current consensus within the research community. Findings suggest that the novel photoreceptor has a different spectral sensitivity to the rod and cone receptor cells connected to the visual system. Early seminal research proposed potential action spectra for melatonin suppression identifying peak sensitivity within a range of wavelengths; 446-477nm (Brainard, et al., 2001b), narrowed further between 457-462nm by Thapan et al (2001) proposing an assumption that peak sensitivity of the novel photopigment was likely to be 460nm. There are three potential explanations as to spectral sensitivity of the novel photoreceptor which mediates non-visual light information to the brain; that the photopigment within ipRGC based on a Vitamin-A opsin molecule has peak sensitivity at 460nm, that this photopigment is more specifically melanopsin with peak sensitivity at 480nm (Berson, Dunn, & Takao, 2002) (Provencio, Rodriguez, Jiang, Hayes, Moreira, & Rollag, 2000) or that there could be multiple photoreceptors involved including the rod and cone cells which would mean the response of the ipRGCs is affected by other wavelengths (Rea, Figueiro, Bullough, & Bierman, 2005) (Bellia, Pedace, & Barbato, 2013) (Enezi, Revell, Brown, Wynne, Schlangen, & Lucas, 2011) (Lucas, et al., 2014).

Although there is greater understanding about the possible connections between these multiple photoreceptive cells within the eye and their individual response to light, at the point of writing there is not a one-dimensional quantity that can describe their interrelation (Lucas, et al., 2014). This might explain why the initial study by Brainard (2001b) into the action spectra for the suppression of melatonin did not find an exact fit with the data. It may also explain why research into the neurobehavioural response to light stimulus has shown sensitivity to long wavelength light as well as short wavelength light. If it is proven that subjective alertness is mediated by the same novel photoreceptor within the eye as the circadian system, the fact that longer wavelength light can elicit the same impact might indicate that a multiple photoreceptor model is more likely, as some researchers suggest (Rea, Figueiro, Bullough, & Bierman, 2005; Rea, Figueiro, Bierman, & Hamner, 2012; Altimus, et al., 2010).

Until more is known about the interrelationships between the multiple photoreceptive cells and the how they influence the non-visual response to light stimulus this thesis will focus on the two possible single photopigment scenarios in terms of spectral sensitivity and the efficiency functions based on them.

4.3.2 Intensity of light

The eye's sensitivity to light for visual tasks is such that it can adapt to a wide range of illuminance reaching its maximum performance rate at a fairly low level of illuminance. Research by Rea et al (1986; 1991) exploring relative visual performance (RVP) has shown that at typical office lighting levels of approximately 500lux on the working plane the visual system is processing light information at near maximal performance. The light intensity required to stimulate other physiological processes such as those connected to the circadian system is less well known with no current consensus as to the exact thresholds necessary.

It has been suggested that the photoreceptors within the eye responsible for non-visual processes have a high illuminance threshold response to light stimulus in comparison to the visual system (Czeisler C. A., 1986; Czeisler, et al., 1989; Badia, Myers, Boecker, Culpeper, & Harsh, 1991; Rea, Bullough, & Figueiro, 2002). Research suggests that many if not all of these non-visual responses to light are processed through the same retina-neural pathway (Klein & Moore, 1979) (Aschoff, 1981). However it is not yet clear whether these non-visual responses are sensitive to the same light intensity threshold. Research within the area of photobiology has been progressing towards identifying these individual threshold sensitivities. For the design of interior environments to begin to respond to the needs of the circadian system as well as support visual performance the necessary thresholds need to be understood. This section will provide an overview of some of the research and draw conclusions as to the potential intensity thresholds required.

4.3.2.1 Melatonin suppression

Melatonin is present within the body in preparation and during sleep and the suppression of this hormone is seen as the clearest evidence of the level of potency of any light stimulus. Initial research followed the premise that a high intensity light was necessary to stimulate a response from the non-visual system. One of the first studies into the intensity threshold for the suppression of melatonin concluded that it is necessary for bright light to exceed a minimum threshold of >2500lux to suppress melatonin (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980). This suggested that the threshold for light intensity is substantially greater than that for the human visual system and therefore normal internal illuminance levels would not be sufficient for melatonin suppression. Similar studies have been undertaken with subjects in extreme environmental conditions, where lighting could be totally dependent on artificial sources, such as at the Antarctic Research Centre. The findings emphasised the fact that changes in circadian rhythms such as the regulation of the hormone melatonin are light

intensity dependent (Broadway, Arendt, & Folkard, 1987). In this study bright light (2500lux) phase advanced melatonin rhythm when administered in the morning and delayed the rhythm when administered in the evening.

Following the study by Lewy et al (1980) a number of further studies showed high illuminance levels reduced melatonin to daytime levels (McIntyre, Norman, & Burrows, 1989) (Bojkowski, Aldhous, English, Franey, Poulton, & Skene, 1987). As Rea (2002) states with a potential threshold requirement of around 10,000lux based on these findings typical office lighting levels of 500lux would not be effective on the suppression of melatonin. However further investigations have shown that a lower illuminance can also have an effect depending on the wavelength suggesting that the spectral distribution of the light in combination with the intensity influences the impact of light stimuli on these non-visual responses.

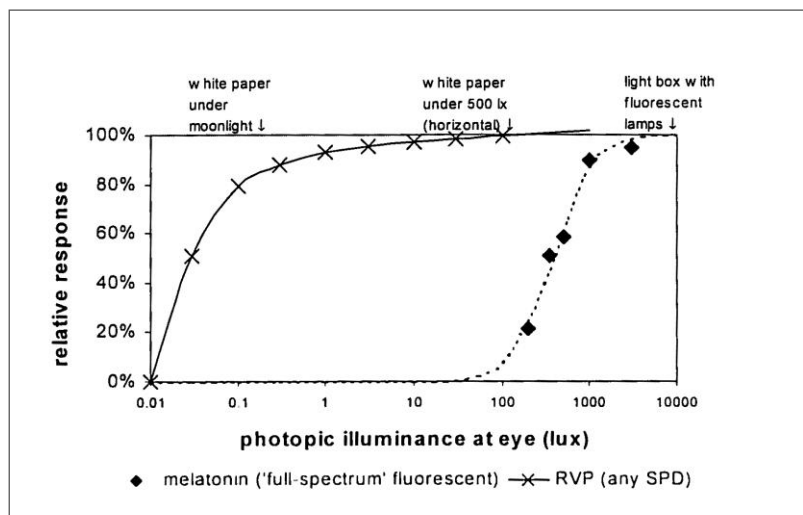


Figure 4.15: Graph showing illuminance against visual performance and suppression of melatonin (Rea, Bullough, & Figueiro, 2002)

In the study by McIntyre et al (1989) which explored the level of acute melatonin suppression during night-time hours, based on a range of illuminance levels, identified similar dose-response results as reported by others (Rea, Bullough, & Figueiro, 2001; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). The findings show that although melatonin suppression begins to be stimulated at the 100lux level (equivalent to 500lux on the horizontal work surface) 50% relative response is not registered until approximately 500lux illuminance level at the eye. Maximal stimulation, defined as 90%, is not reached until the illuminance reaches 1000lux suggested to be equivalent to 2500lux at the work surface. These results were observed using a 3000K fluorescent lamp as a light source. Rea et al (2002) show these

findings overlaid on data from two studies (Rea, 1986; Rea & Ouellete, 1991) investigating relative visual performance, discussed earlier, which clearly indicates the difference between threshold stimulation levels between the two ocular systems shown in Figure 4.15.

Zeitzer et al (2000) conducted a study into the sensitivity of the human circadian system to light exposure during night-time hours. In this study subjects were exposed to 6.5h light stimulus at a range of illuminances in the early biological night. Findings showed a dose-dependent response with melatonin suppression observed from illuminances greater than ~200lux whereas there was minimal suppression below 80lux and variable responses between the two illuminances. By fitting data to mathematical models previously proposed to describe the response of the human circadian system, they were able to suggest that half maximal melatonin suppression could be achieved with approximately 50-130lux. They also suggested that as the findings show a saturation point (90% of maximum) at approximately 200lux that this is well within the range of ordinary room lighting. These results show a non-linear relationship between illuminance and the suppression of melatonin as shown in Figure 4.16.

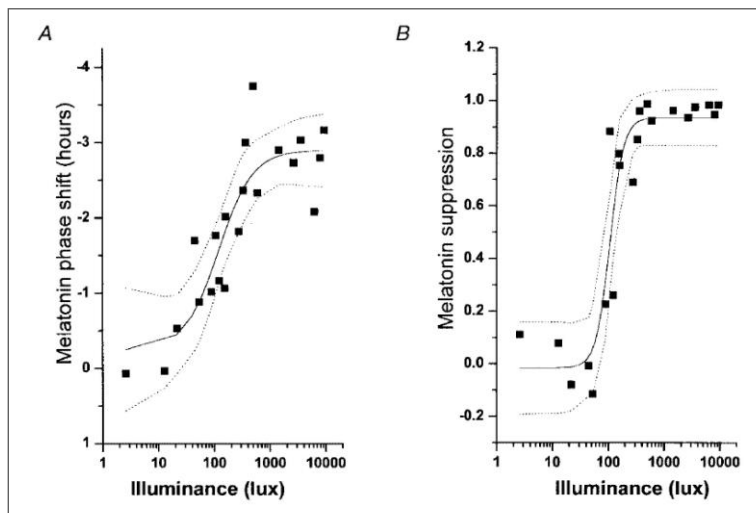


Figure 4.16: Illuminance response curve for melatonin suppression for a 6.5h period of light exposure taken from Zeitzer (2000)

As the researchers note these findings need to be considered in reference to the length of time the subjects were exposed to light. This does not show whether the point at which saturation occurs remains the same with different

durations of light exposure. It should also be considered that light exposure took

place at a time during the circadian cycle which is most potent for melatonin suppression but not a common time for most people to experience long periods of light exposure.

There are discrepancies across the research community as to the intensity of light needed to suppress melatonin. It is unclear whether it would be possible for lower light levels typical to internal room lighting to suppression or whether higher illumination in the order of >1000lux would be required. A report by International Commission of Illumination (CIE, 2004) suggests

that an explanation for the discrepancy between the different intensities of light proposed by research studies could be related to the timing and duration of exposure in relation to the circadian cycle. Also it should be taken into consideration that a good number of the investigations into the illuminance required to stimulate melatonin suppression were undertaken during night-time hours when melatonin levels are generally at their greatest and a reduction is most evident. This also suggests this is the time at which light stimulation is most potent where melatonin suppression is achieved with lower illuminance levels therefore lower illuminance levels may elicit a similar effect as greater illuminance levels.

4.3.2.2 Circadian phase-shifting

Human circadian rhythms were not originally believed to be sensitive to light with the synchronisation of the 24 hour system thought to be triggered by behavioural activity such as social interaction or activity levels (Wever, 1979). An early study by Czeisler et al (1986) investigated the impact of 4h bright light exposure on the circadian system in an elderly woman to establish whether light had a direct effect, independent of other external triggers such as behavioural activity. Using core body temp and cortisol levels as markers they took measurements before and after light exposure discovering that exposure to bright light in the evening induced a 6-hour delaying shift of her circadian cycle. The unexpected results in terms of magnitude of response, rapidity and stability of the shift challenged the existing concepts regarding circadian phase-resetting in humans.

A number of studies have since shown that the human body clock is sensitive to phase-resetting of light stimuli and that there is a non-linear dose-response relationship (Czeisler C. A., 1986; Dijk, Kronauer, Brown, & Czeisler, 2000). Once it was concluded that light was the main external trigger for phase-resetting it was hypothesised that high illuminance values were also necessary as was shown with the suppression of the hormone melatonin. Research with bright light stimuli has shown that high levels of illuminance can phase shift the body's circadian rhythm when administered to counteract jet-lag (Boulos, et al., 2002) or even to improve disturbed sleep/wake patterns amongst astronauts (Whitson, Putcha, Chen, & Baker, 1995). These scenarios occur where external activity confuses the endogenous or inherent rhythm of the body clock.

Following on from research previously undertaken by Czeisler et al (1981), Boivin et al (1996) looked to investigate the validity of the hypothesis that the human circadian system was in fact insensitive to standard indoor illuminance from artificial light sources. Although the sample size had been small the earlier study by Czeisler et al had concluded that a light level as dim as

100-500lux could reduce night time levels of melatonin. Boivin et al (1996) also concluded that even though the effect was proportional to the intensity of light a standard indoor illuminance of 180lux could phase advance the human circadian system. They claimed that they had produced the first dose-response curve of photic resetting of human circadian system. Using core body temperature as an indicator of the effect of light they identified that the impact of light stimulus was proportional to one third the power of light intensity. In this study subjects were exposed to 5h bright light stimulus during biological night-time. It is therefore plausible that low levels of light stimulus would have an impact.

Middleton, Stone & Arendt (2002) also investigated the difference between low and high intensity lighting on human circadian phase entrainment testing two groups of volunteers in a 12:12h light/dark cycle, a scenario which is more relevant to a standard daily pattern. Low light levels of <8lux were used at night and light exposure of either 200 or 1000lux during the day with all temporal cues removed. The subjects exposed to 1000lux showed no signs of needing to delay their sleep patterns unlike the subjects that were exposed to 200lux. The subjects being tested under 200lux significantly extended their sleep in the morning hours, and therefore reduced the length of daily light exposure compared to the subjects exposed to 1000lux. Middleton et al (2002) concluded that these subjects were not exposed to enough light to reset their circadian phase to the 24 hour day/night cycle as shown in Figure 4.17. Physical activity was ruled out as having an effect on the difference between the two groups as neither group took part in a significant amount of exercise during the study. This study shows that a continuous 200lux light exposure during the day similar to standard indoor lighting environments does not entrain the circadian phase, whereas 1000lux does provide enough stimuli. However it does not identify the exact illuminance threshold such that it could be somewhere between these two illuminance levels. The effect of a series of illuminance levels would need to be investigated within this project protocol in order to a more detailed picture of the necessary stimulation threshold.

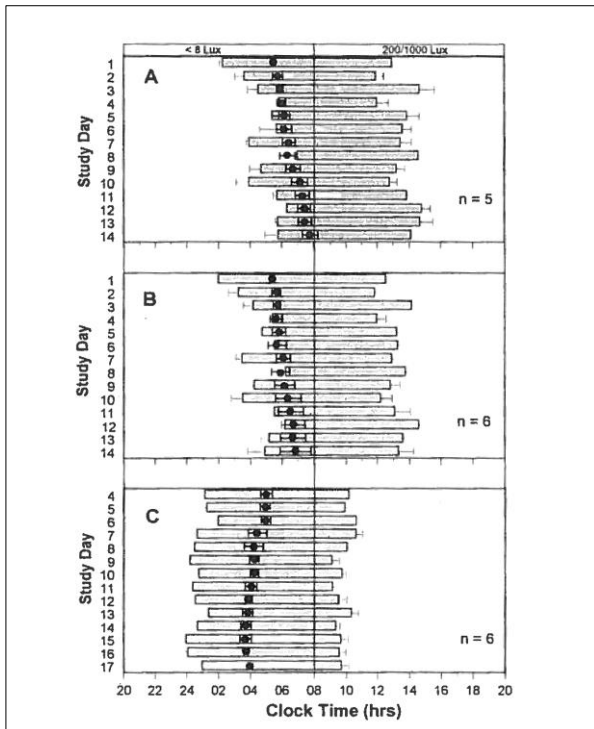


Figure 4.17: Circadian phase response to two different 12:12h light/dark cycles taken from Middleton et al (2002)

As Middleton et al (2002) summarise, the shift in the circadian rhythms of the subjects was due to the intensity or the duration of the light stimulus. Their research also suggests that if the intensity of light was shown to be the main factor, normal illuminance in some building contexts is insufficient to maintain circadian phase position, if there is a lack of other time cues available such as scheduled activities. This scenario, although not likely to affect people who have a consistent activity pattern based around regular working hours, may affect those who are less physically able such as the elderly or patients in hospital for extended periods of time.

Zeitzer et al (2000) used a range of illuminance levels from 3 to 9000lux to establish whether the human circadian cycle is susceptible to low illuminance light exposure during the early biological night. They suggested that the research provided evidence that the human circadian system is sensitive to small changes in light received at the eye during the early biological night such that approximately 550lux would produce a maximal response shown in Figure 4.16. As described earlier they also noted that this could be produced by typical room lighting. In another study by Cajochen et al (2000) it was also concluded that a maximal response for circadian phase-resetting was achieved with light stimulus at approximately 300lux and a half maximal response with light stimulus between 80-160lux. These values are more in line with those recommended for visual performance. It is however necessary to take into consideration that this study like many others was undertaken during the subjective night,

therefore the response achieved may partly be a result of the increased sensitivity of the eye at this time. Melatonin suppression is also used as the main circadian marker in most of these studies, such that the amount of melatonin present within the body will indicate which phase the subject was currently in. This brings into question whether light stimulus is having a direct affect on circadian phase-setting or whether it is an indirect response to the regulation of melatonin.

One way to separate the effect of light stimulus on circadian phase from the suppression of melatonin would be undertake an investigation during the day. Other than the study by Middleton et al (2002) described above there are few studies which examine the phase-shifting affect of light during the day. One study by Jewett et al (1997) suggests that the circadian system is sensitive to light stimulus throughout the day almost irrespective of the intensity. They administered bright light stimulus of ~10,000lux for periods of 5h at different times throughout the subjective day, outside the critical region³ to see the impact it would have on shifting the circadian phase. Following previous studies which had been undertaken with a background illuminance of approximately 100-150lux they also compared measurements with two different background illuminance levels, a dim light of 10-15lux as well as 150lux. This comparison highlighted that the background light plays a part in the direction and amplitude of circadian phase-shifting; the authors suggest this shows that all light stimuli that people are exposed to during the day has an effect on circadian entrainment. Jewett et al (1997) conclude that it would be possible to achieve a phase advance or delay with exposure to bright light during the early and late phases of the subjective day respectively. However they do not recommend a threshold illuminance level that would be necessary to achieve this, only that it would be possible to achieve with sunlight during the earlier part of the day at least. This therefore suggests that it needs to be a high illuminance level.

A more recent study by Zeitzer et al (2011) showed that human circadian phase-shifting can be directly affected by light stimulus when there is no perceptible change in melatonin levels within the body. This therefore suggests that light stimulus can have an effect on the human circadian system directly, unconnected to the suppression of melatonin. This suggests that the non-visual responses to light, although likely to be controlled via the same neural pathway may

³ The 'critical' region is described as the period approximately 1.5h either side of the minimum core body temperature which typically occurs in the early hours of the subjective morning. This period has been shown by previous studies to be most potent to the amplitude of circadian phase-shifting.

have different dose-response relationships. The development of these studies is important as it further narrows the lighting requirements to support these inherent physiological processes.

Circadian phase-shifting has been shown to be achieved with bright light stimulus anywhere from 1000-10,000lux but that there is a non-linear dose-response rate where lower levels of illuminance such as 180lux also elicit a noticeable effect on circadian phase-resetting. The findings from these studies also suggest that the dose-response rate of circadian phase-entrainment is also connected to other factors such as timing and duration of the stimulus. Studies undertaken during night-time hours have shown that phase-resetting can be achieved with lower illuminance levels than originally thought. This may have a direct correlation to the fact it is the time at which the circadian system is most susceptible to light exposure. The study by Middleton et al (2002) in particular suggests that with a more typical day/night routine light exposure needs to be higher in order to entrain the circadian cycle. It is more common for people to be exposed to light stimuli during typical daytime or waking hours than during the night with the exception of those that work night shifts. At these times of day a higher illuminance level may be required to achieve the same effect on circadian phase-shifting.

A lower illuminance level may also elicit an effect with a longer period of exposure as many of these studies have administered light stimuli for between 4-7h periods. Other findings have shown that shorter periods of time can also have a similar effect if higher illuminance levels are used. The impact of length of exposure will be discussed in more detail later but it seems evident that there is an inherent connection between the effect of illuminance level and the duration or length of time a person is exposed to light stimuli.

4.3.2.3 Subjective alertness

An early study into the effect of bright light on subjective alertness during night-time hours was undertaken by Badia et al (1991). They were looking to see the immediate effects of light exposure on psychophysiological and neurobehavioural responses such as changes in body temperature, alertness and performance of behavioural tasks. Although some of the markers used could be connected to circadian phases the study was more interested in the immediate response of the subjects rather than the effect on the phasing. The study showed that bright light between 5000-10000lux had a greater effect on alertness during night time hours than exposure to dim light of 50lux. They also found that performance of tasks was better under bright light exposure than the dim light during the night. Badia et al (1991) concluded that bright light might be used to improve alertness for those working during the night but that a

'light intensity by alertness' function should be determined in order to establish the most efficient intensity levels. This study, although identifying the difference between bright light and dim light did not provide enough specificity as the light stimuli were too far apart.

Cajochen et al (2000) look at the relationship between light intensity and these other neurobehavioural responses such as alertness. Considered as a non-circadian process they were keen to see if there was any correlation between the responses of circadian systems and the response of neurobehavioural processes to light stimulus. An exact dose-response of these neurobehavioural variables had not previously been identified which Cajochen et al suggest might be due to the limited range of light intensities tested within previous studies, as well as not taking into consideration the time at which the subjects were exposed to light. They proposed that night-time exposure to a typical room light level of approximately 90-180lux can have an alerting effect in humans but the magnitude of the response is dependent on the intensity of the light stimulus. They concluded that the findings showed that the half-maximum alerting effect of light was achieved with illuminance between 90-180lux whereas the half-maximum effects for melatonin suppression was achieved between 50-130lux and the circadian phase resetting achieved between 80-160lux.

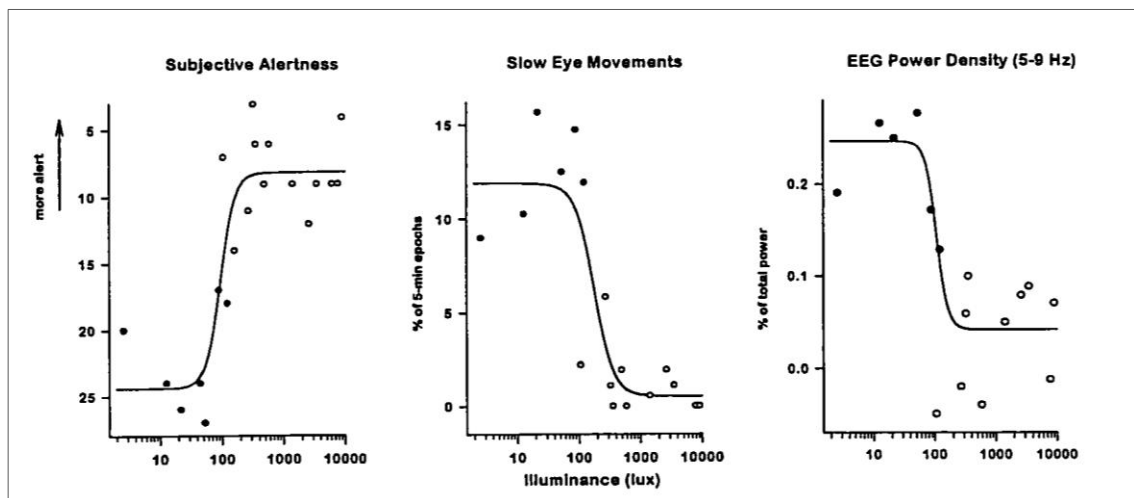


Figure 4.18: Dose-response relationship between illuminance and subjective alertness, incidence of slow eye movements and EEG activity taken from Cajochen et al (2000)

The findings may also suggest that as the dose-response curve for both alerting effects of light and circadian responses are similar, that they are transduced by the same receptors within the eye and the signals are sent using the same neural pathways to the brain. Cajochen et al (2000) make a further assertion that if the non-visual system does not exhibit adaptation to previous light, that it does not maintain a light history, the findings from this study could have a major implication. It would suggest that even though people may have been exposed to

higher illuminance levels within the day a low level illuminance could have an effect on their alertness in the early night-time hours. This in turn could have an impact on their ability to perform tasks, their productivity and potentially their safety. This study like many others is limited to night-time hours and does not assess the effect of light during the day.

Phipps-Nelson et al (2003) carried out a study to investigate the daytime alertness of subjects exposed to dim and bright light. Their findings showed that an illuminance of 1056lux was necessary to maintain subjective alertness which is substantially more than was evident in studies undertaken during the subjective night. The study also showed that there was no correlation between subjective alertness, recorded by response to a psychomotor vigilance test and salivary melatonin. There was no significant difference between the bright light (1000lux) group and the dim light (5lux) for this circadian marker. This study was undertaken specifically at a time when internal melatonin levels are normally low and established that there was an effect on alertness from exposure to light independent from the regulation of melatonin. Although there needs to be further investigation in this area it has shown that the intensity of light is positively correlated to an increase in daytime alertness therefore emphasising the importance of providing interior lighting environments which support non-visual processes.

This evidence implies that there is a strong connection between the intensity of light stimulation and the timing during the circadian phase at which it is received. To be able to design a space which provides the appropriate environment for non-visual processes, the ability of the occupant to maintain alertness could be significant particularly when considering specialised or high-risk tasks.

4.3.2.4 Conclusions for intensity of light

The research outlined above suggests that investigations into the intensity threshold necessary for stimulation of non-visual response to light are currently inconclusive. Although the findings suggest that the non-visual system requires a higher illuminance than the visual system there is some uncertainty as to the exact illuminance levels needed. As many of these studies use different testing parameters it has also shown that there is a relationship between these different parameters such as illuminance level and length of exposure resulting in an effect on stimulation. There appears to be a non-linear correlation between illuminance level and both immediate and phased physiological responses to light exposure as shown in Figure 4.18 from the study by Cajochen et al (2000). This seems to the case for both phased responses to light

exposure such as those connected to circadian cycles as well as the immediate response seen with melatonin suppression as well as subjective alertness measures.

However it is necessary to acknowledge that a large number of the laboratory research to date has been undertaken during subjective night-time when the greatest impact of light exposure can be observed but not necessarily typical within the daily lifestyles of most people. For example the use of melatonin suppression as the biological marker for investigating the relevant dose-response may not be as relevant to daylighting design as this hormone is not prevalent during daytime hours. This is also acknowledged by Anderson et al (2012) in reference to defining a framework for predicting the non-visual effects of daylight to support the design of lighting within the built environment. As Jewett et al (1997) showed when assessing the illuminance-response of circadian cycles described above, light stimuli to which people are exposed throughout the day could have an effect on non-visual response.

It is also apparent that different non-visual responses, either physiological or neurobehavioural could have different stimulation thresholds for light intensity even if these differences are potentially small. There is evidence to suggest that this difference relates to whether the response is immediate such as the affect on subjective alertness or phased relating to the entrainment of the circadian cycle. Night-time melatonin suppression is often used as a marker for the impact of light on the human circadian system but investigations comparing the response of melatonin suppression with the phase shifting of the circadian rhythm have shown that the two response thresholds may differ slightly; Zeitzer et al (2000) identified ~550lux for phase shifting, ~200lux for melatonin suppression. This might suggest that the suppression of melatonin is more sensitive to light and a response may be seen quicker whereas the response of the circadian phasing is a longer term response, effects observed from 2-3 days following light exposure.

Intensity is also dependent on the percentage response that is required. Findings from various studies can differ by log magnitude stimulation such as the difference between Rea et al (2002) suggesting 1000lux at the eye is necessary and Cajochen et al (2000) suggesting 180lux is sufficient to elicit a response. This difference could be explained by the percentage impact on physiological response, Rea et al looking for maximal response but if as Cajochen suggests there is a non-linear relationship between intensity and impact, 50% could be sufficient. There is currently no consensus amongst the research community as to the necessary level of stimulation to maintain well being of the human circadian system. This thesis will assume a

maximal response is necessary such that it incorporates the worst case scenario for the lighting environment in that more light is required rather than less.

This research emphasises the difference between the visual and the non-visual systems. The visual system has a wide range of adaptation to light intensity within which it can still perform various tasks although it reaches its maximum performance rate at a fairly low level of illuminance. Research into relative visual performance (Rea, 1986; Rea & Ouellete, 1991; Boyce, 2003) has shown that at typical office lighting levels of approximately 500lux on the working plane the visual system is processing light information at near maximum performance. It might be that the non-visual system also has a range albeit that it is much narrower but this not yet conclusive from the research.

Until the evidence of the required intensity thresholds for non-visual processes are agreed it may be more appropriate to assume a range within which these responses will be stimulated. These threshold values appear to differ slightly depending on the specific response as identified in Table 4.1 below.

Table 4.1: Proposed illuminance threshold for a range of empirical studies described in 4.3.2

Non-visual	Author	Intensity	% stimulation	Light source
Melatonin suppression	Czeisler et al 1981	100-500lux	Not stated	Not stated
	McIntyre et al 1989	500lux	50%	3000K fluorescent
	ibid	1000lux	~90%	ibid
	Zeitzer et al 2000	200lux	~90%	Cool-white
Circadian phase shifting	Jewett et al 1997	7,000-10,000lux	Not stated	Cool-white fluorescent
	Middleton et al 2002	1000lux	Not stated	Full spectrum lamps (Osram
	Zeitzer et al 2000	550lux	~90% maximal	Cool-white
	ibid	~100lux	half maximal	ibid
	Cajochen et al 2000	80-160lux	half maximal	4100K fluorescent (Philips Color 840)
	Boivin et al 1996	180lux		Cool-white fluorescent (NA
Alertness	Badia et al 1991	5000-10,000lux	Not stated	Cool-white fluorescent (40W)
	Cajochen et al 2000	300lux	~90% (maximal)	4100K fluorescent (Philips Color 840)
	ibid	90-180lux	half maximal	ibid
	Phipps-Nelson et al 2003	1056lux	~90% (maximal)	Fluorescent lamp Thorn 2 L (36W)

4.3.3 Timing

As the research into the illuminance response of non-visual processes suggests the effect of light stimuli has been shown to be dependent to a certain degree on the time at which it is received at the eye and more specifically the part of circadian cycle during which it is received. Studies of the dose-response to light have shown a non-linear relationship between intensity and phase shifting of the circadian system (Boivin & Czeisler, 1996). This is to such an extent that it has been shown that half the maximal resetting response achieved by a light intensity of 9100lux was achieved by just 1% of this light (approx. 100lux) when it was administered in the delaying phase of the subject's circadian cycle (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000).

As described earlier physiological processes connected to the human circadian system have their own inherent cycles such as the obvious sleep/wake cycle as well as core body temperature and hormone release. The peak and troughs of these cycles occur at different times throughout the 24hr day suggesting that each rhythm may be susceptible to external triggers at different points or phases in the cycle. As described in 4.3.2 the majority of investigations into the effect of light exposure on non-visual processes have been undertaken during night-time hours with a limited number of studies investigating the impact of light during the subjective day. Research undertaken to establish the impact of light on circadian phase shifting have shown differing responses at the early and late phases of night-time hours suggesting a differing temporal dimension of the response to light exposure. This could have an impact on different lighting environments provided within buildings particularly in very urban areas where there is continuous illumination throughout the day and night. It also has an impact on those people who do shift work for which they need to be awake and alert at night and sleep in the daytime.

4.3.3.1 Melatonin suppression

The secretion of the hormone melatonin by the pineal gland begins during the early evening with one of its main effects being increased sleepiness. Even though it has an endogenous cycle, in order for physiological processes within the body to be connected to the 24h day/night cycle of a given geographical location one of the strongest external cues is light as discussed above. Therefore it is logical that the regulation of this hormone is significantly influenced by the timing of light stimulus and that certain phases of the cycle are more sensitive than others. Investigations have shown that melatonin rhythm and external light stimuli mediate biological day length adjusting to seasonal changes. This was shown in a study

with researchers based at the Antarctic Research Centre (Broadway, Arendt, & Folkard, 1987) where there are significant changes in the daylight hours between winter and summer months. Bright light of 2500(lux) was shown to phase advance melatonin rhythm when administered in the morning and delay it when administered in the evening.

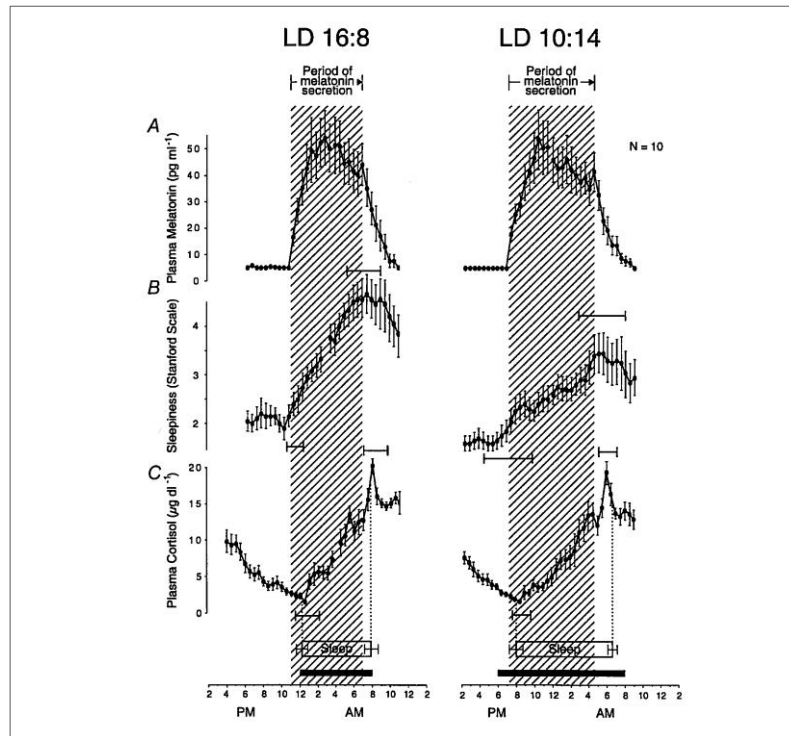


Figure 4.19: Morning and evening transitions in circadian rhythms separately entrained to dawn and dusk taken from Wehr et al (2001)

Wehr et al (2001) showed that when the period of light exposure was controlled, either extended or shortened at the end of the day or at the beginning it had differing effects on the timing of secretion and suppression of melatonin. Melatonin secretion was most susceptible during transition from light to dark period and suppression most susceptible to the dark to light transition period but that the effects were not connected. They showed that adjusting the timing of light exposure had an effect on the regulation of the hormone. The secretion was more susceptible to light in the early biological night and suppression more sensitive to light at the late biological night/early morning as shown in Figure 4.19.

Wehr et al suggest that this data support the notion that the circadian system in humans is defined by the dual oscillator model, where one oscillator controls the onset of melatonin within the body and one controls the offset. This is a suggestion which is supported by others (Warman, Dijk, Warman, Arendt, & Skene, 2003). These dual oscillators have been described

as the M (morning) and E (evening) oscillators and have been shown not to work in parallel to one another. This is in turn related to the influence of light at different times of day.

4.3.3.2 Circadian phase-shifting

Probably the most significant impact of timing of light exposure is seen with circadian phase-shifting, where exposure at different times throughout the day can have a different effect on various circadian rhythms. This includes the sleep/wake cycle, core body temperature and hormone regulation. It has also been shown to be different depending on the person and whether they are more susceptible to light stimulus at one time rather than another, sometimes described as being a morning or evening person (Roenneberg, Wirz-Justice, & Mellow, 2003). As described earlier each circadian rhythm has its own endogenous cycle with peaks and troughs which repeat every 24h approximately, these cycles can be set within the subjective day/night period and often interact with one another. The light we receive in the early morning hours as the sun is beginning to rise, following the nadir of our core body temperature, could be important to advance our circadian phase back in line with a 24hr cycle. It is unclear whether this phase resetting of the circadian system is directly linked to the suppression of melatonin, mediated by the same neural pathway and if so which is dominant.

In the study by Boivin et al (1996) subjects were exposed to 5h bright light stimulus centred 1.5h after core body temperature (CBT) minimum which usually occurs 1-2h before habitual wake time. This part of the circadian cycle has been shown to be the most susceptible to phase shifting by light stimulus therefore it is plausible that low levels of light stimulus would have an impact. In terms of the built environment this is relevant to those scenarios where the occupant may be exposed to light during the second part of subjective night-time through to early morning. This would be most relevant for those people working a night shift or in an environment where there is often a constant level of light throughout day and night such as in a hospital. It is less relevant to those people that have more regular sleep/wake patterns in tune with the night/day cycle of their geographical location and are not subject to light stimuli at night-time.

The effect of different timing of light exposure was tested by Czeisler et al (1989) by administering periods of 5h bright light exposure of 7000-12000lux at different phases of the circadian cycle. The study used a three phase cycle of ordinary room light (100-200lux) during

the scheduled wake times, a period of bright light stimulus (7,000-12,000lux⁴) and darkness (<0.02lux) during the scheduled sleep times. The 5h period of light stimulus was compared with a 5h period of darkness or ordinary room light. The greatest effect on phase shifting was observed with the bright light stimulus administered at the core body temperature minimum, a phase shift of 10.7h was seen in one subject across 2-3 days. It was also observed that ordinary room light exerted an influence on the direction and amplitude of phase-shifting depending on the timing of exposure in reference to bright light stimulus. Czeisler et al suggest that this shows it is possible to shift the human circadian system with a scheduled cycle of ordinary room light, bright light and darkness which had previously not been thought possible and propose it as a solution for those people suffering with jet lag. This is how a common technique for those recovering from trans-world travel.

Khalsa et al (2003) identified the clearest phase response curve (PRC) of the human circadian system using a single bright light (approx. 10,000lux) exposure period of 6.7h administered at different points across the circadian cycle. Light exposure before critical phase at core body temperature minimum caused a phase delay whereas light exposure centred after critical phase resulted in a phase advance. No adjustment of the circadian phase was observed when light exposure was centred at the critical phase. This phase response curve is shown in Figure 4.20 below which is double plotted. They note that this supports a type 1 PRC in contrast to previous studies which have shown a strong type 0⁵ PRC (Czeisler, et al., 1989) where large phase shifts were observed when light exposure was centred near the core body temperature minimum or critical phase. They suggest that this is consistent with their suggestion that humans are capable of both type 1 and type 0 resetting of circadian cycles and that the response is dependent on the intensity of light exposure. Although transitions between phase advance and delay were more gradual during the subjective day the results did not identify a period of light insensitivity or 'dead zone' during the day which has been suggested by others. Khalsa et al (2003) suggest that the pattern of daily light exposure to bright outdoor illumination or indoor artificial light during the day and night significantly contributes to the timing and entrainment of the circadian pacemaker.

⁴ This illuminance level for the bright light stimulus was chosen as an equivalent to natural sunlight just after dawn.

⁵ A type 0 phase response curve produces phase shifts as large as 12 h following light exposure in the critical region whereas type 1 produces phase shifts as small as 0 h in the critical region.

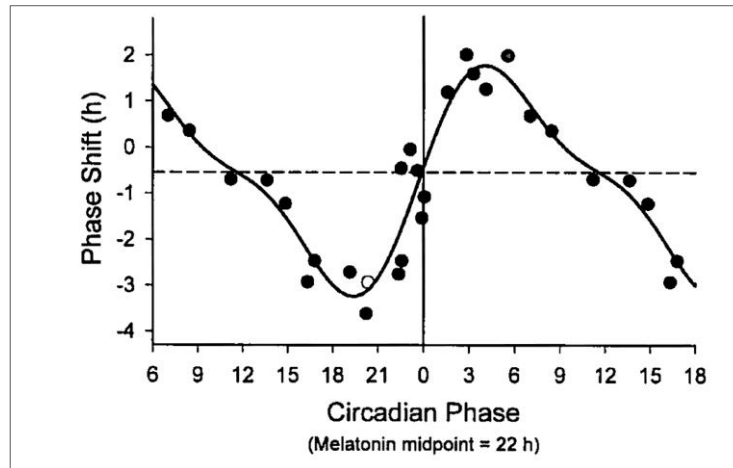


Figure 4.20: Phase response curve to bright light stimulus using melatonin midpoints as the circadian phase marker taken from Khalsa et al (2003)

A study by Jewett et al (1997) also showed that the human circadian cycle is sensitive to light stimulus throughout the 24h cycle with no significant dead zone. The study administered 5h phases of bright light (approximately 10,000lux) stimulus at different circadian phases throughout the subjective day outside the critical phase, within 1.5-22.5h after core body temperature minimum. The results showed that there was no period where light exposure did not have an effect on entrainment of circadian phase and there were no transients⁶ observed following light exposure. Using core body temperature as the circadian marker they observed moderate advances in circadian phase when light stimulus was administered during the first 8h of the subjects' habitual waking day. They also observed small to moderate delays with exposure to bright light stimulus within the last 8h of the habitual day and both these sets of phase resetting occurred within 2-3 days of light stimulus. Their comparison of off-centre and centred bright light stimulus where the light exposure was set within a greater background light of approximately 150lux instead of the dim light (10-15lux) showed that the background light interacted with the bright light stimulus whether it was administered early or late within the day. They proposed that this suggests that the phase-resetting response is light dependent rather than behavioural, connected to scheduled light stimulus rather than the controlled timing of sleep/wake cycle.

Jewett et al (1997) concluded that human circadian phase entrainment was affected by any light stimulus that people are exposed to throughout the day. This would also mean that

⁶ Transients are described as non-steady state behaviour following exposure to a phase-resetting stimulus (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997).

human circadian phase-resetting could take place without affecting the habitual sleep/wake pattern and is therefore separate and distinct to the presence of melatonin within the body.

4.3.3.3 Subjective alertness

The findings from investigations in to the effect of light stimuli on alertness are less conclusive than those focused on other physiological processes such as melatonin suppression. This has been suggested by some to be a symptom of the inconsistencies between trial parameters (Jung, et al., 2010) such that there have been a wide range of light intensities tested as well as duration of light exposure and timing at which it was administered. Conducting unbiased studies where immediate changes in alertness can be established as being directly influenced by light exposure and not affected by other parameters is also difficult due to the obvious nature of the study. In their dose-response investigation Cajochen et al (2000) showed that light exposure administered during the early biological night could elicit an immediate alerting response. This response was assessed through measures such as EEG activity, subjective sleepiness as well as a reduction in the incidence of slow eye movements. This study showed a positive correlation between the alerting response and the percentage suppression of melatonin which Cajochen et al suggest emphasises the fact that these two physiological responses are mediated by the same mechanisms within the eye and brain.

As discussed above the level of the hormone cortisol is highest within the body just before habitual wake time and is connected to increased alertness. Investigating the effect of light on cortisol levels within the human body Jung et al (2010) showed that light exposure of approx. 10,000lux reduced cortisol levels when administered during the night (the ascending phase of cortisol cycle) and in the morning (the descending phase of cortisol cycle). The control study using continuous dim light appeared to have no effect on cortisol levels in comparison. The findings showed that during night-time exposure to light, cortisol levels decreased significantly starting approximately 2.5hr after the beginning of light exposure but returned to normal levels quickly afterwards. This suggests there was no delaying effect on the circadian phase. Light exposure during the early daytime also showed a significant reduction in cortisol levels starting approximately 1h after the beginning of the light period and remained at this level for the first half of the period of light exposure but returned to normal levels in the second half. Jung et al suggest this may be because this is a period of the circadian phase which is less sensitive to light exposure.

The study by Phipps-Nelson et al (2003) outlined above is one of very few studies to look at the daytime affect of light exposure on non-visual processes such as alertness. Controlled bright light of approximately 1000lux was administered between midday and 5pm in comparison to a dim light exposure of <5lux as a control. Using measures of subjective alertness (Karolinska Sleepiness Scale, KSS) as well as performance (Psychomotor Vigilance Test, PVT) the results showed that there was a significant improvement in subjective alertness in the group exposed to bright light in comparison to those who were maintained in the dim light environment. The improvement in subjective alertness has been linked to the suppression of melatonin during night-time light exposure but this study did not identify any changes in saliva melatonin levels. Even though the investigation was undertaken at a time when melatonin levels are inherently low within the human body the absence of any change indicates that the immediate response of subjective alertness may not be directly connected to the presence or lack of melatonin in the body. Phipps-Nelson et al (2003) show that there is a potential affect of bright light exposure during day time hours on behavioural and psychophysiological responses as well as during the night.

These results slightly contradict the findings from an earlier study by Badia et al (1991) which administered alternating periods of bright light (5,000-10,000lux) and dim light (50lux) and compared it to continuous bright light and dim light exposure. They found that although there was an improvement in night-time alertness with the alternating bright light and dim light there was no significant improvement in daytime alertness. This study might suggest that the behavioural and psychophysiological responses are not susceptible to bright light during the day or that the combination of duration of exposure as well as timing is more significant at this point in the 24hr day.

The study by Phipps-Nelson et al (2003) highlights the potential significance of the lighting environment people are exposed to during the day in particular if much of that day is spent inside with limited or no access to the high illuminance and broad spectral distribution of daylight. During the winter months it is common for a large percentage of people to drive to and from work in the dark and then spend the rest of the day under light of no more than 300lux, a typical lighting level within an office environment. Only being exposed to this level of illuminance during the day could have a detrimental effect on their circadian system.

4.3.3.4 Conclusions for Timing

Unlike the human visual system which responds similarly to light stimuli at any time of day or night, the response of the non-visual system is differentially sensitive to light depending on time of day. Due to the different circadian rhythms that have their own inherent phases the potency of light collected at the eye and transmitted to the brain is significantly dependent on timing. For example the phased response to light of the sleep/wake cycle is particularly sensitive to light exposure in the early biological night as well as the early morning. Khalsa et al (2003) showed a clear phase response curve for human circadian phase which highlighted the impact of light administered before and after core body temperature minimum which typically occurs 1-2hrs before habitual wake time.

Therefore light exposure in the early to mid morning (6am to 10am) assuming habitual wake time is typically 7-8am can phase advance the circadian system meaning that habitual wake time is brought forward. A greater percentage of people have an endogenous circadian cycle which is greater than 24hr and therefore needs entraining to the day/night cycle with a phase advance. If significant light exposure occurs in the early biological night speculatively between 6pm and 6am there is a likelihood that the circadian phase would be delayed which would delay onset of sleep. This in turn could disrupt the natural sleep/wake cycle which often happens to those that regularly work during night-time hours, or even late into the evening. With the exception of those who chose to work during the biological night, in order to sustain circadian well being it is important to maintain a regular light/dark routine avoiding substantial light exposure during the early biological night. As it has been suggested that the circadian system is controlled by a dual oscillator (Wehr, Aeschbach, & Duncan Jr, 2001), one for the onset of melatonin and one for the offset it may also be necessary for some people to be exposed to sufficient light in the early morning in order to advance their circadian phase.

Jewett et al (1997) suggest that the circadian system is also sensitive to light exposure during the day and that moderate phase advancements can be achieved when sufficient light is received during the first 8hr of habitual daytime. They also suggest that a similar affect on phase delay can be achieved with light exposure during the last 8hr of habitual daytime. Although the subjective day may not have the same potency as night-time hours this would suggest that the period of time when the human circadian system is susceptible to light stimulus stretches further into the day. This would potentially mean that human circadian phase-resetting could take place without affecting the habitual sleep/wake pattern and is therefore separate and distinct to the presence of melatonin within the body.

Disruption to the circadian system could have a detrimental effect on the lives of those people who are exposed to significant light during night-time hours whether this is through night shift work or within an environment where high illuminance levels are maintained throughout the day and night such as hospitals. Although light exposure can delay the circadian phase, adaptation to a different schedule can take a number of cycles or 24hr periods. As Boyce (2003) represents with a graph taken from a study by Monk et al (1978) in which the adjustment of the circadian phase over 21 night shifts, adaptation to the ideal phase can take a number of days. As shown in Figure 4.21 the graph represents the difference between the ideal phase for the shift being worked and the actual circadian phase of the individual based on core body temperature. It isn't until around the 15th night-shift that the actual circadian phase reaches a complete adaptation.

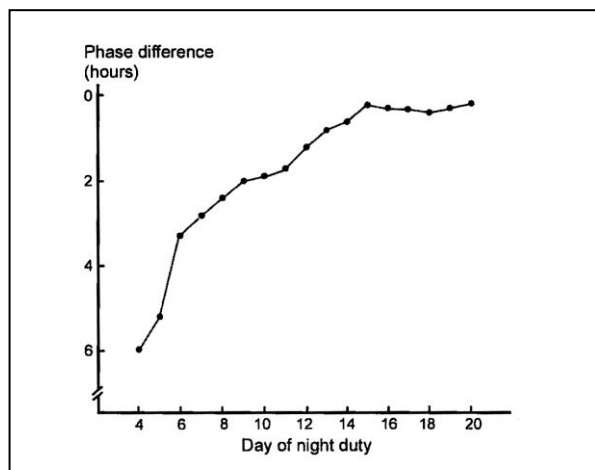


Figure 4.21: Circadian phase adjustment over 21 night shifts (Boyce (2003) after Monk 1978)

The more immediate neurobehavioural responses such as alertness have been shown to be positively correlated to the circadian cycle of melatonin regulation and as such follow a similar PRC. This neurobehavioural response has also been shown to be sensitive to light exposure more directly and in particular during the daytime (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003). Therefore light exposure during the daytime between midday and 5pm could lead to an immediate improvement in alertness. These findings suggest that light exposure throughout a 24hr period can have an effect on non-visual processes mediated by the eye depending on the particular process. This has implications for the design of lighting environments of the buildings people live and work within. At some point of the day or night, depending on the activity pattern of a given individual, it will be necessary for their brain to receive sufficient light information to trigger a range of non-visual processes.

4.3.4 Length of exposure

The visual system has a relatively quick response time or adaptation to light stimulus, which is perceptible when moving from a brightly illuminated environment to one which is less bright or in darkness. The human visual system collects light stimulus from both the rod and cone photoreceptors which means that it can perform in a wide range of lighting environments. The length of exposure necessary for the visual system to respond to a given lighting environment is fairly short anything from a matter of seconds to a number of minutes depending on the magnitude of change (Boyce, 2003). As there is no current consensus as to the specific parameters of light that result in non-visual responses to light, the exact characteristics of the response time or the length of exposure to elicit a response is unclear.

The majority of research into the characteristics of the human non-visual mechanisms have focused on the intensity, spectral quality or timing of light with very few looking to compare the length of exposure or duration of light stimulus. A large percentage of the findings relating to the duration of light stimulus required are an output of studies looking at the wavelength sensitivities of the non-visual system. Most of these studies utilise monochromatic light administered with artificial sources at night so it seems plausible to predict that the response could be different using polychromatic light or even from long term exposure particularly during the day as suggested by Anderson et al (2012). This section will look at research which identifies the potential duration thresholds for light exposure to stimulate the physiological and neurobehavioural responses.

4.3.4.1 Melatonin suppression

Lewy et al (1980) first showed that bright light exposure can begin to have a suppressing effect on melatonin levels within 10-20mins and reduce melatonin levels to near daytime levels within an hour when administered during the melatonin release phase or biological night. Further studies were undertaken by McIntyre, Norman, Burrows & Armstrong (1989) to establish the degree to which melatonin levels are suppressed by light exposure. They observed that the brighter the light stimulus administered at the eye of the subject the quicker the suppression of melatonin occurred. The findings of these two studies were summarised clearly in a graph presented by Rea et al (2002) in their review of the potential for a new circadian photobiology, see Figure 4.22 below. This shows the relationship between the time melatonin could be measured and the illuminance at the eye based on three different levels of melatonin suppression, 25%, 40% and 50%. Based on findings from these two studies, with a constant illuminance at the eye greater than 1000lux a 25% suppression of melatonin could be

measured within 20mins but that if illuminance at the eye was 200lux, melatonin suppression greater than 25% is unlikely to occur no matter the length of exposure. These results also suggested that to achieve 50% suppression of melatonin exposure to light stimulus for at least 30mins would be necessary even with a high illuminance level.

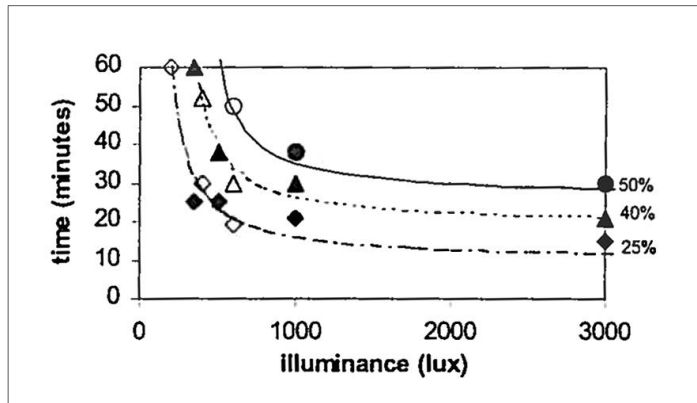


Figure 4.22: Graph showing the time required to observe melatonin suppression against the illuminance level of light stimulus (from Rea (2002)after McIntyre (1989))

A fact that is apparent across these investigations is the intensity of light necessary to trigger the threshold is linked to both the timing and the duration for which it is administered; therefore these parameters are inextricably connected. Research has shown that exposure to a longer period of light at a lower illuminance approximately 100lux has produced 50% the response of light nearly 100 times the intensity, (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). These findings show the significance of further investigation into the impact of different illuminance intensities combined with the duration of exposure and the connection this might have with the time of day or night.

4.3.4.2 Circadian phase-shifting

Zeitzer et al (2000) showed that light stimulus administered during early biological night could have an impact on circadian phase even at fairly low illuminance levels with duration of light exposure which was quite long at 6.5hrs. As outlined above they showed that approximately 100lux could achieve half maximal response of much higher illuminance levels of 9000lux approx. Khalsa et al (2003) also used a 6.7h period bright light which consisted of alternating 6min intervals of fixed gaze with approximately 10,000lux stimulus and free gaze with approximately 5000-9000lux stimulus. Both these studies incorporated fairly long episodes of light exposure whether it was a single illuminance or an alternating pulse which highlights that longer duration of light stimulus can have a significant impact on phase shifting the circadian cycle. It was suggested by Khalsa et al (2003) that using a longer period of exposure may

however mask the presence of a period of insensitivity or a 'dead zone' particularly during the subjective day.

To investigate the boundaries of the circadian sensitivities to duration of light stimulus it is important to look at the extremes. It has been suggested that there is an effect on resetting the circadian phase at the very beginning of a period of light exposure (Forger, Jewett, & Kronauer, 1999) and that further extension of this light exposure would produce minimal additional phase shift. Gronfier et al (2004) tested this theory with a study to compare a single phase of intermittent bright light pulses with exposure to continuous bright light during early biological night, approximately 3.5h before core body temperature minimum. Both bright light stimuli were approximately 9500lux administered for a period of 6.5h with the intermittent exposure being 15min light pulses separated by 60mins of dim light (<1lux). Although the intermittent bright light exposure only amounted to a total of 1.5h bright light stimulus, 23% of the continuous episode, it had a similar impact on delaying the circadian phase. Gronfier et al (2004) note that if these results were compared on a per minute basis the delaying effect of the intermittent bright light exposure would be 3.2 times greater than the continuous bright light exposure. This suggests that shorter periods of light exposure could potentially be used to reset the circadian phase.

Kronauer et al (1999) produced a mathematical model to predict the response of the human circadian system to light exposure. From this model it emerged that there was inherent threshold duration of 5-10min for bright light pulse with a max period of 80min darkness in-between which was necessary to achieve a full effect on the circadian system. It also showed that if the illuminance level of the light pulse was reduced the period of time necessary to elicit the same response needed to be increased. This further emphasises the connection between the length of exposure and light intensity.

A physical investigation into the impact of short flashes of bright light was undertaken more recently by Zeitzer et al (2011) in which short millisecond flashes of light were administered once per minute for a period of 60mins during a period in the early biological night. Findings from this study suggest that it was possible to detect a delay to the circadian phase following this short period of light exposure. Zeitzer et al suggest that the human circadian system is capable of integrating these really short periods of light, only 0.12sec in total, across a much longer period. A phase delay of 45min (+/-13min) was observed following the short flashes of light. Zeitzer et al (2011) compared this response with that from a previous study by Chang et al (2011) where a continuous exposure to 10,000lux elicited an 82min delay suggesting that

the short flashes of light had achieved 45% of the phase shift seen with light exposure 20 times brighter. Compared with an earlier study by Zeitzer et al (2000) where a continuous period of 6.5h light exposure achieved a delay of 154mins it suggests that the shorter flashes of light over a period of an hour could achieve approximately 30% of this shift in the circadian phase. Although these findings might provide a potential treatment for sleep disorders often suffered by those who work during the biological night it is not characteristic of the lighting environment experienced by most people.

4.3.4.3 Subjective alertness

As other research has shown the effect of light exposure on subjective alertness follows an immediate behavioural and psychological response rather than phased response as with other circadian cycles. In this respect instead of seeing an effect after one or more cycles, a response to light exposure is seen immediately within the same cycle. It is therefore reasonable to assume that the length of light exposure necessary to elicit a response would be shorter than needed to observe response in phased circadian cycle such as the sleep/wake cycle. As with other lighting characteristics the sensitivity of the response may also depend on the timing at which the light is administered and in that way the length of exposure necessary will vary depending on the time of day.

A number of studies have looked at subjective alertness when light is administered during the night as this part of the circadian cycle has been shown to be most sensitive to light exposure for other physiological responses. Cajochen et al (2000) showed that 6.5hr of light exposure during the early biological night can have an alerting effect even at a low illuminance level. These results show that a fairly long and continuous period of light exposure can have an effect on subjective alertness but it is not clear from this study whether there is a threshold for duration of exposure as they did not test a range of exposure lengths. In another study Cajochen et al (2005) showed that a 2hr period of light exposure during the late evening or early biological night can have a positive effect on alertness. As this study was looking to establish the spectral sensitivity of this behavioural response it also did not include a range of light exposure durations so it is not possible to establish a threshold from these findings only that a shorter exposure length elicits a positive response. However it is also important to acknowledge that this study utilised monochromatic light sources comparing 460nm and 550nm so a response may have been detected due to the increased potency of the shorter wavelength light in particular. This also does not give a realistic picture of the exposure to polychromatic light that most people would experience in their daily lives.

Extremely short exposure to light during night-time hours has also been shown to have an effect on the immediate response of alertness in parallel to a phased effect circadian system as discussed above (Zeitzer, Ruby, Fiscaro, & Heller, 2011). The study administered 60 2-msec flashes of light (473lux) over a period of an hour during the night equated to 0.12sec of light exposure over the hour. Zeitzer et al (2011) propose that this study shows that the mechanisms involved in non-visual processes such as subjective alertness have an ability to integrate short exposures to light over a period of time, such that a sequence of brief light exposures are interpreted more as a continuous exposure. It is not currently known whether this is something that happens in the ipRGCs or the SCN but it is not a response that is observed in the visual system. This study by Zeitzer et al was undertaken during the biological night as with many of others at a time known to be potent to the human circadian system. The findings relating to the length of exposure may therefore be heavily influenced by the timing of light exposure.

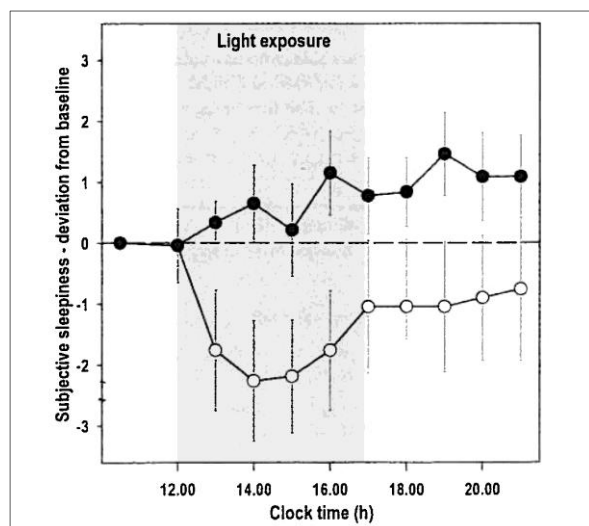


Figure 4.23: Mean deviations from baseline of subjective sleepiness scores based on Karolinska Sleepiness Scale for daytime bright light (open circle) and dim light (closed circle) exposure taken from Phipps-Nelson (fig1) (2003)

There are not many studies that examine the affect of any lighting characteristics on non-visual responses during day-time hours but one study by Phipps-Nelson et al (2003) did look to establish the connection between. In a comparison between bright light (~1000lux) and dim light (<5lux) administered for a continuous period of 5hr during the subjective daytime

(12.00 – 17.00) they showed that this exposure to bright light had a significant effect on subjective alertness. This conclusion was based on the response

to the Karolinska Sleepiness Scale (KSS) and Psychomotor Vigilance Task (PVT) performance shown in Figure 4.23 and Figure 4.24 Although this study was not looking to establish the threshold for duration of light exposure and therefore did not examine a range of exposure durations looking at the findings does give an impression of the magnitude of response based on the length of time.

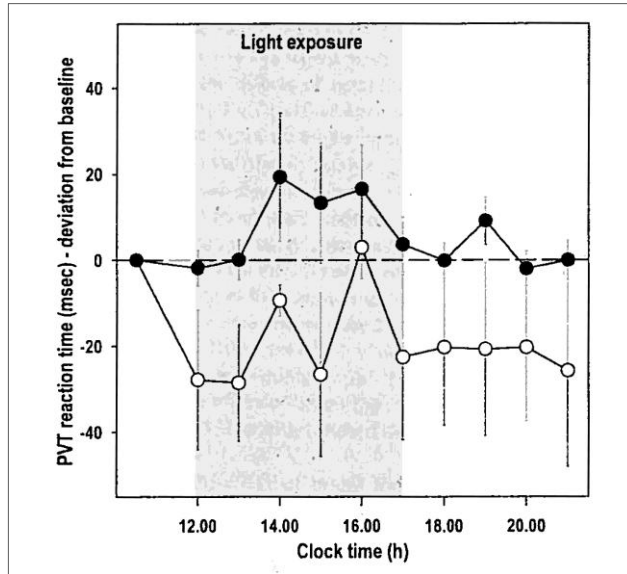


Figure 4.24: Mean deviations from baseline of reaction time (PVT) performance in milliseconds for bright light (open circle) and dim light (closed circle) exposure taken from Phipps-Nelson (fig.2) (2003)

Looking at the KSS scores in Figure 4.23 highlights that after an hour of light exposure the mean deviation decreases to around -2 relative to the baseline result. This subjective sleepiness rating only decreases further to approximately -2.25 from the baseline throughout the full 5hr period with the nadir occurring at 14.00, 2hrs after the beginning of light exposure. It could be suggested from this that the greatest response to light exposure when measured by subjective sleepiness happens during the first

2hrs of light exposure. The results from the PVT performance results suggest a similar conclusion in that the greatest reduction in response time from the baseline occurred during the first 2hrs of light exposure as shown in Figure 4.24. This measure shows a more immediate response from the start of light exposure with an immediate reduction in reaction times to approximately -25-msec from the baseline result. This score does not improve throughout the 5hr light exposure period suggesting that the first 1-2hrs are the most potent in terms of PVT performance. Although this study by Phipps-Nelson (2003) was not looking to establish the threshold for the duration of light exposure the results do suggest that the initial period of 1-2hrs is the most potent for day-time impact on alertness.

4.3.4.4 Conclusions for Duration

Although the length of light exposure is the least well understood of the stimulation characteristics for non-visual responses it is clear that longer exposures are required than for the visual system. As outlined more recently by Lucas et al (2014) the make-up of the novel ipRGCs lack the specialised cell organ present in rod and cone cells that improves the quantity of light captured. Lucas et al reference research by Wong et al (2012) which shows that this results in the probability of an ipRGC detecting a photon of light energy being more than 1million times lower than that of the rod and cone cells. This in turn means that it could take longer to reach the threshold of light necessary to activate than it does to activate the visual system.

In order to fully understand the required length of exposure necessary to stimulate the various non-visual mechanisms it is necessary to better understand where phototransduction occurs, whether it is at the photoreceptor itself or further along the neural pathway. For example it may take a greater amount of time to activate the photopigment within the ipRGC but a quicker response may be achieved where the photic information terminates. If this is the case it would support the notion that multiple photoreceptive cells provide light information to the ipRGCs and in turn the brain. This might explain why the research outlined above shows both an immediate reaction to fairly short periods of light exposure for example for the suppression of melatonin (Lewy, Wehr, Goodwin, Newsome, & Markey, 1980) (Rea, Bullough, & Figueiro, 2002) as well as longer exposure to achieve significant phase-shifting of the circadian system (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997) (Khalsa, Jewett, Cajochen, & Czeisler, 2003) (Gronfier, Wright Jr, Kronauer, Jewett, & Czeisler, 2004).

However this seems to be a simplification of the evidence as it is also evident that there is a relationship between illuminance level and the duration of light exposure necessary to elicit a response for both immediate and phased processes. As well as this connection there is also an obvious relationship between the length of exposure and the time at which it is received most evident by the impact on the phase-resetting of the circadian system (Khalsa, Jewett, Cajochen, & Czeisler, 2003). There are periods of the circadian phase when light exposure is more potent than at other times but whether this is an intrinsic quality of the ipRGC or of the neural mechanisms involved in the regulation of these physiological processes is unclear at this stage.

The required threshold for length of exposure to light might come back to where the phototransduction for these non-visual mechanisms takes place. It has been shown that ipRGCs have the capability once activated to maintain a continuous signal to the brain but the duration of light stimulus necessary to elicit a response from the brain may vary in length depending on the physiological or neurobehavioural function. It might in fact be detrimental to certain mechanisms to be exposed to long periods of light for example disruption to the circadian cycle from light exposure during night-time hours. Studies into the response of neurobehavioural mechanisms such as alertness also suggest that the first 1-2hr of light exposure have the most potent effect with little improvement across the rest of the period of exposure (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003) (Cajochen, et al., 2005). This is evident with studies during night-time hours as well as during the day; even those studies

investigating the impact of short flashes or pulses of light suggested that there was an integrated or cumulative effect across a longer period of approximately an hour.

In terms of practical application there are a number of potential conflicts such as improved alertness and performance through increased light exposure could be beneficial to those working during the night but could be detrimental to the circadian system and connected physiological processes such as hormone release. Whilst taking into consideration the fact that research in this area is still evolving and there is a lot still to understand about the different mechanisms involved this thesis will assume a precautionary range; at least 20min-1hour light exposure to elicit an immediate response such as an increase in subjective alertness up to 6hr to effect a significant circadian phase shift. It should be noted that this is purely an assumption based on current research to provide the basis for a hypothetical evaluation of lighting environments and will be subject to change based on developments in this area of research.

4.3.5 Summary: Non-visual processes and the brain

The internationally accepted system of photometry does not currently include considerations for non-visual responses to light. Research into the connection between light received at the eye and non-visual mechanisms within the human body has established that there are a number of factors which influence the response; spectrum, intensity, timing and duration. Research also suggests that the required threshold does vary depending on the required response.

This thesis is looking to establish whether the design and specification of glazing systems has an impact on the health and well being of the building occupant in respect of light stimuli therefore the quality and quantity of daylight received is the focus. Using this as a filter to review the research findings outlined above it suggests that circadian entrainment and subjective alertness are the most relevant non-visual processes connected to exposure to light stimuli. Acknowledging the temporal significance of light stimulus as mentioned above this thesis will focus on two circadian indicators that can be connected to the subjective day; circadian phase-shifting or entrainment with early morning light exposure and subjective alertness.

4.3.5.1 Timing and duration

Research outlined above has shown that the circadian system is temporally sensitive to light exposure (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997). Further studies have

also suggested that the circadian system is controlled by a dual oscillator, one diurnal, one nocturnal that are entrained to dawn and dusk respectively (Wehr, Aeschbach, & Duncan Jr, 2001). This mechanism has been shown not to be parallel therefore the effect of light stimulus in the evening and in the morning may not be connected. This suggests that the light received by a building occupant during the early hours of the day could have an impact on their circadian phase irrespective of light exposure in the evening which might primarily be provided by artificial sources. This thesis will assume that light received 06.00-10.00 will have the most potent effect on circadian phase entrainment, advancing or resetting to the day/night cycle of the local context.

The response of subjective alertness to light stimulus during the day has not been widely investigated in comparison to nocturnal studies. Phipps-Nelson et al (2003) showed that light exposure during the day of approximately 1000lux is effective in improving subjective alertness in comparison with low background illuminance levels. This study showed that a 5hr period of light exposure from midday had a positive effect on sleepiness and performance following sleep loss. Although this study did not examine the different light exposure durations it did show that the first 1-2hr of light exposure has the greatest impact on alertness and performance. This supports the notion that the lighting environment people spend the majority of their working day within could have a significant effect on their alertness and performance.

4.3.5.2 Intensity

Research has shown that circadian phase-resetting or shifting has a non-linear dose-response to light intensity. However an exact illuminance threshold has not been defined therefore it seems plausible to assume a range of illuminance values within which a response could be expected. This is an approach taken by other researchers in lieu of a defined threshold (Anderson, Mardaljevic, & Lockley, 2012). Zeitzer et al (2000) propose corneal illuminance saturates for circadian phase resetting at ~550lux, defined as 90% of the asymptotic maximum response. Although this was a nocturnal study based on the research outlined above it could be assumed that the response to light stimulus during the day is mediated by the same neural pathway but that a higher illuminance value is needed to activate a response. Therefore illuminance level proposed by Zeitzer et al for nocturnal activation could be assumed as the lower boundary of an illuminance threshold range.

For an upper boundary it is potentially difficult to limit the range as exposure to daylight during the day and in particular first thing in the morning seems the most inherently natural

way to entrain the circadian system (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997). This would suggest that the upper boundary was anywhere between 7000-10,000lux. Middleton et al (2002) show that following a typical sleep/wake protocol with evenly balanced periods of light exposure and darkness that 1000lux at the cornea maintained circadian entrainment in comparison with an illuminance level more common to internal environments. As it is not currently known whether there is an actual saturation point for non-visual mechanism it may be more feasible to assume this as an upper threshold of this range.

Investigations have shown that subjective alertness also follows a dose-response relationship to illuminance levels similar to circadian phase-shifting. Early studies suggested that high illuminance levels are necessary to elicit a measured effect on alertness during the day (Badia, Myers, Boecker, Culpeper, & Harsh, 1991) but more recently a half maximal response has been achieved with a fairly low illuminance level (Cajochen, Zeitzer, Czeisler, & Dijk, 2000). Following the same approach findings from the nocturnal study by Cajochen et al (2000) that found a corneal illuminance of approximately 300lux achieved a near maximal response which will be used as a lower bound for a response from subjective alertness. The study by Phipps-Nelson (2003) highlighted that a greater intensity of light may be required to maintain alertness during the day with a suggested intensity threshold around 1000lux. This will provide the upper bound to the threshold range for the stimulation of subjective alertness during the day. This set of assumed activation parameters are shown in excluding wavelength which will be assumed as the same for both non-visual processes included in this thesis and will be discussed in more detail below.

4.3.5.3 Wavelength

Until the specific relationships between the multiple photoreceptive cells within the eye are better understood it is difficult to define the exact impact this has on the spectral sensitivity of the non-visual mechanisms within the human body. This thesis follows the assumption that this novel photoreceptive cell (ipRGC) is sensitive to short wavelength light as agreed by the majority of the studies outlined above. Circadian efficiency functions have been proposed based on empirical data from Brainard (Brainard, et al., 2001b) and Thapan (Thapan, Arendt, & Skene, 2001) as well as Enezi (Enezi, Revell, Brown, Wynne, Schlangen, & Lucas, 2011) which suggest peak sensitivity of 460nm and 480nm respectively. This thesis will include both possible single photopigment scenarios in terms of spectral sensitivity and the efficiency functions based on them.

The characteristics of the dose-response function for subjective alertness is similar to that for melatonin suppression and phase shifting which may suggest that they are mediated by the same photoreceptors in the eye and retinohypothalamic pathways that mediate the circadian responses to light (Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Figueiro, Bierman, Plitnick, & Rea, 2009; Rautkylä, Puolakka, & Halonen, 2012). It is assumed in this thesis that the spectral sensitivity for subjective alertness is the same as for circadian responses until there is more conclusive evidence to the contrary.

Assumed activation parameters are shown in Table 4.2 excluding wavelength which will be assumed as the same for both non-visual processes included in this thesis and will be discussed in more detail below.

Table 4.2: Assumed activation parameters or characteristics for circadian phase-shifting and subjective alertness

Non-visual response	Intensity		Timing	Duration
	Lower threshold	Upper threshold		
Circadian phase-resetting	550lux	1000lux	Early subjective morning 06.00 – 10.00	2 hr
Subjective alertness	300lux	1056lux	Subjective day 12.00 – 17.00	1-2 hr

Although evidence does suggest that both circadian or phased responses to light and the more immediate response such as subjective alertness are mediated by similar neural pathways this is inconclusive, with no singular set of parameters agreed with the possible exception of spectral sensitivity. This thesis will assume a set of lighting parameters for each response which will be used to assess the specification of glazing components for the design of daylight spaces. As it is also currently unclear as to the level of activation needed to maintain these non-visual mechanisms, whether maximal saturation is necessary or 50% is sufficient this thesis will assume maximal values to provide a worst case scenario (generally assumed as approx. 90% saturation). It may be shown at a later date that 50% activation or even 25% is sufficient in which case the model can be adjusted to reflect this.

As the biomedical research is incomplete at this stage it has been necessary to make some assumptions about the activation parameters for non-visual processes connected to the eye. They are not intended as exact figures but a basis from which to assess light provided within an internal environment.

4.4 Implications for daylight design

There are very few studies undertaken to date that examine the potential impact of light stimulus during the subjective day and the associated impact on non-visual responses acknowledged in a recent review by Anderson et al (2012). This means that there is generally not a great understanding of the impact the design of the lighting environment has on the well-being of the occupant beyond visual performance. As shown by the research outlined above light received during the day could have an effect on the ability to align the human circadian phase with the 24hr day/night cycle. This could in turn affect physiological processes such as sleep/wake times, core body temperature and hormone regulation. Daytime lighting environments could also have a more immediate effect on neurobehavioural responses such as subjective alertness and performance. The findings have shown that both the circadian and neurobehavioural responses to light are differentially sensitive at certain times of the day and night which may also be interrelated to other parameters such as length of exposure and quantity of light.

The design of a building to acknowledge the changing needs of the people that inhabit it throughout the day should therefore include the lighting environment. The orientation of the building is significant for a number of other design parameters including the control of solar gain and thermal performance but it may also need to be considered in respect to the arrangement of spaces within the building. As the timing of light stimulus has been shown to be important the lighting environment within the rooms people inhabit during specific times of the day will also be important. Considering the contribution of daylight this could be influenced by the position of the space within the building, the orientation of the window wall as well as the glazing specification.

As Anderson et al (2012) suggest the level of light necessary to entrain or shift the circadian rhythm could be greater during the day than at night due to the general light level to which people are exposed. Another possible scenario may be that all light received by the eye contributes to the entrainment of circadian rhythms (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997) therefore to see a marked change there would need to be a significant amplification of the light stimulus. The human circadian system may also have a higher threshold to light intensity during the day which has been acknowledged by some (Rea, Figueiro, Bierman, & Hamner, 2012). The greater intensity of light provided by daylight could in principle provide the necessary light stimuli to support the non-visual system.

During the day it should be possible for people to receive enough light at the eye to support these non-visual processes from daylight. As the visual system can adapt to a wide range of illuminance levels it may not always be apparent to the individual that they are not receiving enough light. This could also be compounded by the fact that the lighting environment is being delivered by an artificial source and therefore not providing the right quality or wavelengths of light to which the non-visual system is sensitive.

As outlined in Chapter 2 lighting guidance provided for the design industry is driven by the human visual system and illuminance levels necessary to perform visual tasks. As the area of research around non-visual response to light is still evolving, exact thresholds for the activation of these mechanisms has not been agreed therefore the established system of photometry currently does not take these other parameters into consideration. The difference between the parameters for visual and non-visual responses to light suggest that as well as the potential need for a higher illuminance level the photoreceptor cells involved have different sensitivities to the wavelength of light received. The current method of measuring light is fundamentally linked to the sensitivities of the human visual system such that it does not provide an accurate picture of the effectiveness of the light to stimulate a non-visual response such as from the circadian system.

4.4.1 Circadian efficient lighting

Recommendations and guidance have traditionally looked to provide the optimum lighting environment for performing a variety of visual tasks working with findings from the large amount of investigative studies into the human visual system. If it is proven conclusively that the light stimuli for the circadian system are different to those which provide information to the brain about the visual surroundings it will be important to establish the correct lighting environment for this system to work at its best. The research outlined above suggests this set of parameters may be very different to the optimum characteristics for visual performance.

A number of researchers have developed models to try and define circadian efficient lighting in order that the lighting industry can respond to the additional lighting stimuli needed for other physiological processes. Bellia et al (2013) suggests that there two different approaches for the definition of a circadian lighting model; a model of circadian photometry based on a proposed sensitivity function, from data such as Brainard (2001) and Thapan (2001) such as the models developed by Pechacek et al (2008) and Gall & Bieske (2004), and a second approach based on human neurological response to light such as the suppression of

melatonin. An example of this second approach is proposed in theory by Rea et al (2005), the model was then used by Bellia (2013) for an evaluation of the effectiveness of classroom lighting environments. This section will give a brief overview of the possible approaches used to define circadian efficient lighting and the implications on daylighting design.

4.4.1.1 Circadian luminous efficiency

Light, although quantifiable is not like any other physical entity as it is entirely defined by the sensitivity of the human visual system to radiation at a certain part of the electromagnetic spectrum as discussed in Chapter 2. In order to provide a mechanism to connect units of light to other measures such as Watts the International Commission on Illumination (CIE) determined a physical definition of light; 1 Watt radiant flux at a wavelength of 555nm will produce 683 lumens, the constant lumens/watt value is therefore 683lm/w for the CIE Standard and Modified Photopic Observers. The luminous efficacy of a light source is determined by how many watts per lumen it produces based on the sensitivity of the human visual system, or more specifically the response of the cone photoreceptors defined as photopic illuminance. Based on the photopic luminous efficacy function defined by $V(\lambda)$ and the constant lumens/watt value determined by CIE it is possible to define the spectral luminous efficacy for a given wavelength of light, described in Equation 4.2 below

Equation 4.2: Spectral luminous efficacy function

$$\text{Spectral luminous efficacy} = K_{\lambda} = K_m V_{\lambda}$$

Where;

K_m is 683/lm (max. sensitivity for photopic vision which occurs at 555nm)

V_{λ} is the value of the photopic spectral luminous efficiency function for that wavelength

Artificial light sources are defined in part by their spectral power distribution (SPD) which identifies how much light is being produced at different parts of the visible spectrum. Lighting manufacturers often work hard to maximise energy output at the parts of the spectrum most potent for the visual system, described in more detail in Chapter 5. This system of photometry, based on the sensitivity and response of the photopic visual system, does not take into consideration the sensitivities of the circadian system and the stimulation characteristics for which the spectral distribution of light is important discussed above.

A large percentage of studies into the sensitivities of the non-visual system to date use artificial light sources due to the greater level of control they provide. The quantity of light provided within these investigations is given in a variety of units but mostly in illuminance or

lux, a measurement which is specific to the visual system and not necessarily descriptive of the circadian impact. To understand the circadian response it is therefore necessary to equate this quantity of light to circadian efficient light stimulus. Artificial lamps also produce energy across the visible spectrum in an irregular pattern depending on the process by which they create light, this is particularly apparent with fluorescent lamps. The photometers used to record light levels within experiments will generally have been calibrated with a photopic luminous efficiency function, weighted to the human visual system, the lux measurement itself having a weighting towards visual sensitivities. Unless the specific light source is indicated, providing the possibility to define the spectral power distribution (SPD), it is difficult to establish the specific spectral distribution of the light received at the eye.

Photometry as described above is weighted towards peak sensitivity of the human visual system at approximately 555nm on the electromagnetic spectrum. If the photoreceptors responsible for sending visual information to the brain were the same as those responsible for transmitting light to the SCN to entrain the circadian system then the 'circadian' strength of a light source could be quantified in photopic lux. Although recent research has suggested that the photoreceptors involved in photopic vision might play a minor role in the circadian process (Rea, Bullough, & Figueiro, 2001; Rea, Figueiro, Bierman, & Hamner, 2012; Rea, Figueiro, Bullough, & Bierman, 2005) there is significant research that indicates the main connection is with a third 'novel' photoreceptor within the eye, as shown above. Therefore measurements of light using a device weighted towards the photopic incident spectrum such as a photometer or luxmeter will also not directly provide information about the efficacy of the light for non-visual responses (Webb, 2006).

The response for non-visual processes such as melatonin suppression, circadian phase entrainment and subjective alertness will differ depending on the light produced within the relevant band of shorter wavelengths potent to the circadian system. This has been described by some as the circadian efficacy of the light source, the ratio to the photopic efficacy, and this has been estimated for different light sources by a number of researchers (Rea, Bullough, & Figueiro, 2002; Pechacek, Anderson, & Lockley, 2008; Bellia, Bisegna, & Spada, 2011). These calculations are based on proposed action spectra for the response of certain circadian rhythms. Although this approach does provide a means by which it is possible to estimate the potential efficacy of a given light source for the circadian system it does not provide a distinct circadian luminous efficiency function similar to the photopic efficiency function.

This definition is constrained by the fact that research in this area of biomedicine and neuroscience is incomplete at this time. However the current research findings suggest that there is strong evidence for important role light plays in the stimulation of other physiological processes and the sensitivities may be markedly different than those of the visual system. The basis for potential systems of circadian photobiology have been proposed by a number of researchers based on the initial findings from empirical studies (Rea, Bullough, & Figueiro, 2002; Anderson, Mardaljevic, & Lockley, 2012; Gall & Bieske, 2004; Pechacek, Anderson, & Lockley, 2008). In order to conclusively define this new model there needs to be international agreement as to the precise performance characteristics of the circadian system. Until this time assumptions have to be made as to the likely thresholds for these lighting parameters from which initial analysis of lighting environments can be made.

4.4.1.2 Circadian prediction model

A relatively recent approach to evaluating the effect of light stimulus on the human circadian or non-visual system is based on detailed exploration of the neurophysiological response. There is growing evidence to support a more complex response to light received at the human retina involving more than one photoreceptor. Inconclusive study data suggest to some researchers that the novel ipRGCs may not be the sole photoreceptor involved in mediating light information to the brain, that there may also be interconnections between the rod and cone cells. This approach suggests a more complex interrelationship between the stimulation thresholds of all photoreceptors within the eye and the response of the non-visual processes such as circadian phase-resetting and subjective alertness.

Based on neuroanatomy and electrophysiology of the human eye and the neural pathways connecting it to the brain Rea et al (2005) developed a possible model for phototransduction. This model furthered work by Figueiro et al (2004) who identified spectral opponency in the suppression of melatonin in which different photoreceptors can be seen to turn on and off when stimulated by light. This showed a connection between certain photoreceptors including the newly identified ipRGCs. The model created by Rea et al predicts that rod cells set the threshold for circadian phototransduction, below a certain intensity of light the response of rod cells to light stimuli inhibits the ipRGCs. They state that rod inhibition not only reduces the overall sensitivity of the circadian system to light but once the rod cells are saturated inhibition to this spectral sensitivity is turned off.

The mathematical model developed by Rea et al (2005) is based on physiological process of melatonin suppression and circadian stimulus and describes the percentage melatonin

suppression a particular light stimulus will achieve based on the response of all photosensitive cells within the retina. Rea et al (2005) acknowledged that there is not enough evidence to be certain whether the other non-visual processes respond in the same way as the suppression of melatonin.

Although inconclusive it takes into consideration what is known about the neuroanatomy of the eye and the electrophysiology of the messages that are sent to the brain. It also acknowledges the findings that suggest multiple photoreceptors are involved in relaying non-visual messages and this could include the classical rod and cone cells. Rea et al, as well as other research teams, propose that the circadian response to light stimulus is not additive and therefore cannot be calculated by simply multiplying the intensity or power of light by the action spectrum and that the necessary stimulus varies from the threshold value for circadian activation to the saturation of circadian response.

Bellia et al (2013) use this method in their study of the effect of natural and artificial lighting in on the occupant within educational environments. The method is based on predicting the percentage melatonin suppression defined by empirical studies of the effect of light on nocturnal melatonin suppression. This calculation takes into consideration the response of four photoreceptors to a given light stimulus; rod response, ipRGC response, S cone response and a joint L and M cone response. The relative spectral efficiencies of these photoreceptors are based on empirical data from Brainard et al (2001b).

This calculation is based on a prediction of the percentage melatonin suppression that would be achieved by a particular light stimulus. These definitions of circadian light and circadian stimulus are defined by current understanding of the suppression of melatonin during night-time hours based on findings of the effect of 1 hour exposure to light near the mid-point of the melatonin phase. In order to use this approach for incorporating circadian efficient lighting thresholds within design guidance, the method would have to assume that the response of all non-visual processes had the same stimulation characteristics as melatonin suppression. It therefore assumes that the light received during the day has the same impact on physiological response as light received at night. Based on current evidence provided by the research outlined earlier this approach would seem to be in doubt at this stage, however with further research from the biomedical community it may be proven to be accurate.

4.4.1.3 'Circadian equivalent' lighting model

Another method to establish the potential of a given lighting environment to stimulate the human circadian system is to convert illuminance levels based on photopic sensitivity to equivalent circadian lux. This approach is based on the proposed circadian efficiency function derived from action spectra established by empirical studies described earlier (Brainard, et al., 2001b; Thapan, Arendt, & Skene, 2001). This is only possible if the spectral distribution of the light reaching the eye is known and a consistent conversion basis is employed. In the study by Rea et al (2002) which described the basis of a framework for circadian photobiology they proposed an estimate of circadian luminous efficacy based on an empirically derived action spectrum for melatonin suppression. In order to be able to equate the circadian efficacy of different light sources it was necessary to develop a method of normalising the lumen output. The relative ratios of 'circadian' lumens to photopic lumens were calculated by normalising to 3000K fluorescent light source.

Table 4.3: Photopic and 'circadian' luminous efficacies according to the empirical function derived from Brainard (2001b)& Thapan (2001)with values normalised to 3000K fluorescent (after Rea et al (2002)

Light source	Photopic luminous efficacy (lm/W)	'Circadian' luminous efficacy (lm/W)	Relative ratio of 'circadian' to photopic lumens
3000K rare earth fluorescent	87 (1.00)	149 (1.00)	1.00
4100K rare earth fluorescent	87 (1.00)	275 (1.85)	1.85
7500K rare earth fluorescent	65 (0.75)	285 (1.91)	2.56
High-pressure sodium	127 (1.46)	115 (0.77)	0.53
Incandescent	15 (0.17)	32 (0.21)	1.25
Red LED (630nm)	44 (0.51)	2 (0.02)	0.03
Blue LED (460nm)	11 (0.13)	681 (4.58)	36.2
Daylight (6500K)	-	-	2.78

The table above proposes the 'circadian lumens' produced by a given light source as well as the ratio of circadian lumens to photopic lumens produced by a number of light sources. This comparison highlights the significant differences between the two values and the potential errors that might occur if a conventional light meter/measuring device was used to characterise input to the circadian system. For example this table suggests that daylight is 2.22 times more effective than an incandescent lamp for the circadian system. It identifies the increase in energy output necessary to provide a suitable circadian stimulus based on the type of artificial light sources used. Rea et al (2002) suggests that slightly higher illuminance in combination with the right SPD for suppression of melatonin should be considered in lighting design. By utilising their circadian luminous efficacy table the comparison of performance of

different light sources suggests that to achieve a 50% response of melatonin suppression using a 3000K fluorescent approximately 500lux at the eye (2500lux on the horizontal plane) for 1 hr is required, but only 300lux at the eye of 7500K fluorescent gives 50% max melatonin suppression. This provides a useful method to compare the circadian efficacy of different light sources against one another which is valuable in the retrospective analysis of a given interior space.

Another approach to this mathematical process was developed by Pechacek et al (2008) where the absolute spectrum of the given light source is multiplied by the 'circadian efficiency' curve $C(\lambda)$ derived from the same empirical data as Rea et al (2002). It is then possible to derive a circadian-lux value for the light source. It is then possible to convert illuminance levels from one source with its own distinctive spectral power distribution (SPD) to 'circadian' efficient illuminance levels by a ratio of efficiency. It is possible to compare the efficacy of light from one source to the equivalent from another. This in turn makes it possible to compare the findings from different light intensity dependent studies of the human circadian system. For example using this mathematical model Pechacek (2008) was able to equate 300lux, defined as the necessary threshold for 100% stimulation of night-time alertness by Cajochen et al (2000) provided by a 4100K fluorescent tube in the study, as equivalent to 190lux for the CIE standard illuminant D65. Following this method they established the equivalent response for a number of light sources both natural and artificial based on an approximated colour temperature shown in Figure 4.25.

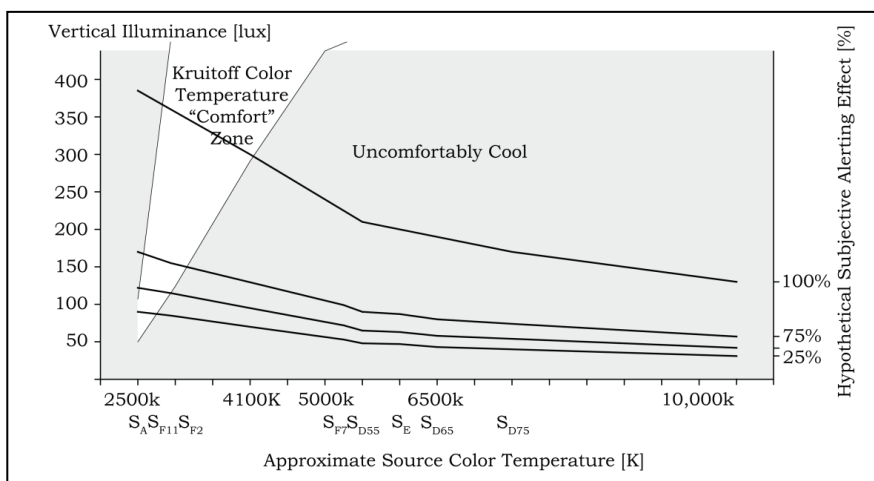


Figure 4.25: Pechacek et al (2008) (fig. 4) representation of alertness benefits from different illuminants by colour temperature based on empirical data from Cajochen et al (2000)

Anderson et al (2012) used this mathematical model and assumptions based on empirical data to derive a threshold range of 'circadian-lux' levels provided by daylight to stimulate the non-

visual system. In order to rationalise the model for use with daylight as the sole light source they approximated each of the three components of daylight (solar beam, overcast and clear sky) to a CIE standard illuminant. They then used this threshold range to set parameters for a non-visual lighting model in order that it would be possible to evaluate workflow simulations in existing buildings.

Bellia et al (2011) established a similar method to characterise the circadian effect of light stimuli based on the visual sensitivity function as well as proposed circadian sensitivity functions. Building on the work by Rea et al (2002), they include three proposed circadian efficiency functions based on different empirical data from the more frequently cited Brainard and Thapan as well as Kozakov (Leukos, 2008) whose findings propose peak sensitivity for the non-visual system at around 450nm. The mathematical process used normalised spectral power distribution of light output is weighted by the circadian sensitivity or efficiency function. Bellia et al (2011) noted that by following this method it was then possible to compare the spectral power distribution of a number of light sources in terms of the visual and the circadian response without the need to introduce luminous flux or the concept of 'circadian lumens'. Based on physical measurements taken with a number of artificial light sources as well as light from the sky vault and direct beam sunlight they developed a series of visual and circadian efficiencies based on the three different efficiency functions shown in Table 4.4.

The process employed by Bellia et al (2011) integrates the electromagnetic spectrum between 380 – 800nm by the circadian efficiency function, derived from empirical findings, and ultimately provides a sum across the visible range as a ratio of the total energy provided by a given light source. On first impressions it seems strange that Bellia et al perform the calculation in this way as it does not identify any differences at specific parts of the visible spectrum. If they had divided the total spectrum between smaller wavelength bands before integrating they may have been able to gain more information about the impact at specific parts of the spectrum. However as Bellia et al were considering the effect of broad spectrum light sources this approach is potentially more realistic as it considers the light source as a whole rather than a sum of the parts or in this case wavelengths bands. Table 4.4 below shows the proposed visual and circadian efficiencies for different light sources based on the three different action spectra.

Table 4.4: Visual and circadian efficiencies for different light sources in the range 360-800nm (after Bellia et al (2011))

Range 360 – 800nm							
Source	V_{VF}	C_{VF} (Bra)	C_{VF} (Bra)/ V_{VF}	C_{VF} (Tha)	C_{VF} (Tha)/ V_{VF}	C_{VF} (Kos)	C_{VF} (Kos)/ V_{VF}
Sunlight	0.25	0.33	1.33	0.42	1.71	0.24	0.96
Sky vault	0.22	0.52	2.34	0.59	2.66	0.46	2.08
Incandescent	0.24	0.22	0.92	0.32	1.35	0.13	0.56
White LED	0.40	0.61	1.52	0.75	1.86	0.47	1.15
Metal halide	0.36	0.45	1.25	0.57	1.59	0.33	0.94
LP sodium	0.51	0.27	0.53	0.46	0.91	0.10	0.20
Fluorescent (warm)	0.47	0.43	0.93	0.61	1.30	0.26	0.56
Fluorescent (cold)	0.36	0.64	1.78	0.76	2.12	0.50	1.40

This table suggests that the cold fluorescent lamp is not too dissimilar from the circadian efficacy of the sky vault. This might seem strange bearing in mind the spectral distribution of this light source. However this similarity may be explained by the fact that cold fluorescent lamps generally produce high photon density at specific wavelengths across the visible spectrum, disproportionately from the rest of the spectrum and even from other broader spectrum light sources such as the incandescent or even white LEDs. This is described by the spectral relative radiance graphs of different light sources measured as part of the Bellia study shown in Figure 4.26. They show the amount of energy produced across the visible spectrum by each light source relative to the rest of the spectrum. When integrating the total energy produced across the spectrum by the chosen circadian efficiency function the fact that cold fluorescents produce a significant amount more energy at particular parts of the shorter end of visible spectrum than other areas provides an explanation as to why the C_{VF} is similar to that of the sky vault in Table 4.4.

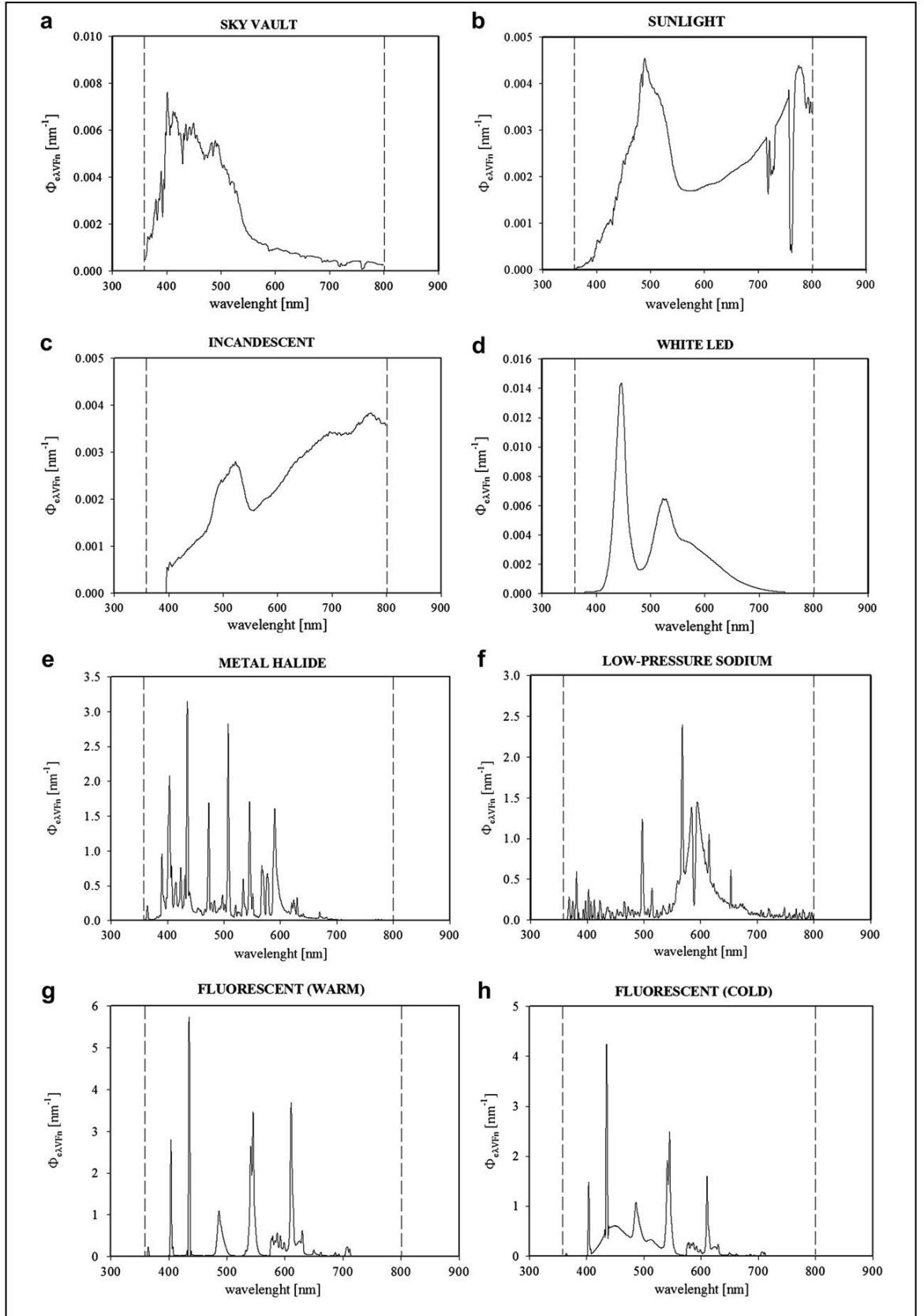


Figure 4.26: Spectral relative radiance graphs of a cold fluorescent lamp, a white LED and the sky vault (after Bellia (2011)).

As well as visual and circadian efficiencies Table 4.4 also includes what Bellia et al suggest is equivalent to the relative ratio of circadian to photopic lumens as described by Rea et al (2002) or 'circadian action factor' relative to each of the three proposed circadian efficiency functions (highlighted in blue). They suggest that this value might be a useful connection between the visual and circadian effect of a given lighting environment. It would also be possible to compare the circadian efficiency of a specified illuminance level from one light source against another. This mathematical approach provides a method by which comparisons can be made of the effect of different lighting environments on visual as well as non-visual responses to light.

4.4.1.4 Summary of circadian efficient lighting

When biomedical research is more complete it will be possible to establish an agreed measure which links light energy to the human circadian system similar to luminous flux. In order to accurately achieve this there will need to be agreement as to the photic response of the novel photoreceptor linked to the non-visual system as well as the relationship with the other photoreceptor cells.

Once a new system of photobiology has been derived it will provide the framework by which lighting environments can be designed to support physiological well-being of the building occupants as well as visual performance. Until this time it will be necessary to make some assumptions as to the response of these non-visual responses to light. It is acknowledged in this thesis that these assumptions are made in order to facilitate an assessment of the design and specification of buildings to support the necessary lighting environment based on empirical data at the time of writing.

In summary of the methods by which circadian efficient lighting can currently be derived, each approach described above has their advantages and disadvantages. Table 4.5 gives a brief summary of these attributes in reference to this thesis.

Table 4.5: Pros and Cons of three different circadian efficient lighting methods

Circadian efficient lighting method	Pros	Cons
1. Prediction model (Rea, Figueiro, Bullough, & Bierman, 2005)(Bellia, Pedace, & Barbato, 2013)	<ul style="list-style-type: none"> Acknowledges potential role for multiple photoreceptors. 	<ul style="list-style-type: none"> Based on empirical data from nocturnal study of melatonin suppression. Single source of empirical data.
2. 'Circadian lux' (Rea, Bullough, & Figueiro, 2002) (Pechacek, Anderson, & Lockley, 2008)	<ul style="list-style-type: none"> Provides opportunity for comparison with photopic/visual response. 	<ul style="list-style-type: none"> Single source of empirical data. Based on circadian efficiency relative to photopic
3. Circadian efficiency factor (Bellia, Bisegna, & Spada, 2011) (Gall & Bieske, 2004) (Wandachowicz, 2006)	<ul style="list-style-type: none"> Multiple sources of empirical data. Provides opportunity for comparison with photopic/visual response. 	<ul style="list-style-type: none"> Based on circadian efficiency relative to photopic Limited light sources included in study

For example, the prediction method described in 4.4.1.2 is based on a detailed approach to the physiological response of the eye to non-visual light stimulus incorporating potential relationships between the different photoreceptor cells. However it is currently modelled on the effect of light stimulus on the suppression of melatonin during night time hours, the relevance of this for other non-visual processes such as subjective alertness has not been confirmed. It also based on the percentage melatonin suppression achieved by a given lighting source which may not at this stage be entirely appropriate to understand the impact of daylight spaces. Although it seems likely that this approach when further developed may give a more accurate picture of non-visual response to light stimulus until a method has been developed to incorporate other diurnal responses to light it is not as relevant for daylighting design.

As there is not an accepted spectral weighting function for non-visual responses this thesis will use the method proposed by Bellia et al (2011), represented as method no.3 in Table 4.5 above, which includes circadian and photopic efficiencies derived from three sources of empirical data; Brainard, Thapan and Kozakov. This acknowledges the fact outlined above and noted recently by a paper by Lucas et al (2014) that it is not yet possible to accurately predict the non-visual impact of a given light source based on its intensity and spectral distribution. Lucas et al and other researchers (Rea, Figueiro, Bierman, & Hamner, 2012)(Bellia, Bisegna, & Spada, 2011) do acknowledge that the science is at a point at which it is possible to start investigating the potential impact on the lighting environment.

The empirical studies described above have provided a range of light intensities that reveal an effect on non-visual processes that occur within the human body based on the well defined system of photometry. As a large percentage of these studies have described the light source that has been used the results are essentially normalised to the characteristics of this light source, in particular to the spectral power distribution. The light source typically used within these studies is a cool-white fluorescent as shown in Table 4.1. Taking the assumed threshold range for light intensity, defined above and given in photopic illuminance levels, and an understanding of the sensitivity of the non-visual processes connected to the eye Bellia et al have derived a circadian action factor. Using this ratio the necessary illuminance level provided by daylight has been derived below based on the three proposed action spectra for non-visual processes and shown in Table 4.6.

Table 4.6: Daylight equivalent illuminance level as defined based on Bellia et al (2011)

	Fluorescent lamp (cold)	Daylight equivalent (Sky vault)		
		C_{VF}/V_{VF} (Brainard)	C_{VF}/V_{VF} (Thapan)	C_{VF}/V_{VF} (Kosakov)
Circadian Phase shifting				
Lower threshold (lux)	550	418	438	370
Upper threshold (lux)	1000	761	797	673
Subjective Alertness				
Lower threshold (lux)	300	228	239	201
Upper threshold (lux)	1056	803	841	710

Within Table 4.6 the lowest daylight equivalent illuminance value based on all three proposed action spectra have been highlighted for the lower thresholds for each non-visual responses. It also highlights the highest daylight equivalent illuminance value based on all three proposed action spectra have been highlighted for the upper thresholds. These values present the widest range of potential upper and lower thresholds for the stimulation of these two non-visual processes and provide a conservative estimate on the illuminance levels necessary.

Establishing this circadian equivalent range of illuminance levels in this way the wavelength or spectral power distribution of light as well as quantity of light has been taken into consideration. By taking these illuminance levels as well as the other lighting characteristics assumed from empirical research described earlier, two sets of lighting parameters have been created; one set for circadian phase-resetting, one for subjective alertness outlined in the Table 4.7.

Table 4.7: Proposed lighting parameters to support two non-visual processes of circadian phase-resetting and subjective alertness.

Non-visual response	Intensity		Timing	Duration (approx)
	Lower threshold	Upper threshold		
Circadian phase-resetting	370lux	800lux	Early subjective morning 06.00 – 10.00	2 hours
Subjective alertness	200lux	840lux	Subjective day 12.00 – 17.00	1-2 hr

This set of lighting parameters provides a basis from which to analyse the potential impact of the lighting environment on the non-visual requirements of the building occupant and will be used later in the thesis.

4.5 Summary and conclusions to Chapter 4

The extensive literature review above highlights that biomedical, neuroscience and chronobiological research into the non-visual effects of light stimulus is currently incomplete. However there is agreement amongst the research community that the eye, as well as capturing visual information, also sends information to the brain which is used for circadian, endocrine and neurobehavioural processes.

Research into the connection between light received at the eye and non-visual mechanisms within the human body has shown that there are four main parameters which influence this non-visual response; spectral quality, quantity, timing and duration. Although the visual and non-visual systems rely on some of the same parameters, such as quantity and wavelength of light, the specific requirements within these parameters are different. For example, research outlined above has shown that non-visual processes are sensitive to a shorter wavelength light than the visual system.

Unlike the visual system, research findings also suggest that the non-visual system is temporally sensitive to light, for example, light received during the early subjective morning or early evening having a greater impact on the circadian phase-resetting. There is growing evidence for a possible link between misalignment of the circadian system due to an irregular pattern of light stimulus leading to the deregulation of hormone release and chronic diseases.

If it is proven by further research that the light received at the eye plays a role in occupant wellbeing, it is therefore plausible to suggest that the built environment, in which most people spend a large percentage of their daily lives, has an impact on the light information received by the brain to stimulate these non-visual processes and in turn their well being. Taking a precautionary approach to understand how the internal lighting environment can incorporate these potential differences could have an impact on the well-being of the building occupant.

In reference to the focus of this thesis, two sets of lighting parameters have been assumed for two non-visual processes shown to respond to light exposure during the daytime; circadian phase-resetting and subjective alertness as shown in Table 4.7. These assumptions provide a basis from which to assess internal lighting environments with respect to the non-visual system and will be carried through into the rest of the thesis. They should not be taken as absolute measures for circadian efficient lighting or the impact on health and well-being. Through further evidence will come greater clarity which will inform the approach taken here.

Chapter 5

The light in our buildings

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5 The light in our buildings

The provision of light is a fundamental requirement of any building interior as it allows the inhabitants to understand and respond to their surroundings as outlined in Chapters 1 and 2. Different visual tasks require different lighting environments and as such a range of performance characteristics for the light provided have been defined in guidance for designers. As Chapter 4 has also identified there is growing evidence that the human body also has requirements for the light information it receives in order to maintain well being, defined in this study as circadian well being or the non-visual effects of light.

Although the manipulation of natural light is an inherent tool of the architect the control afforded by the provision of a cheap energy source has to some extent shifted the balance unevenly toward artificial light sources. The characteristics of artificial and natural light sources are different both in the quantity and quality of light defined by their luminous efficacy and the distribution of energy across the electromagnetic spectrum. The developing body of biomedical research such as outlined in Chapter 4 suggests that to maintain circadian well being the specific characteristics of light received by the eye could be different from those required by the visual system. Therefore those designing lighting environments will need to have a better understanding of what these sources of light actually provide for the building occupant.

This chapter will explore the nature of the light available to designers and occupants of the buildings they design, both artificial and natural. It will draw conclusions about the impact of the variability of the quality of this light on the way lighting designers and architects should go about designing buildings to support the well being of the people that inhabit them.

5.1 What is light?

Light is a form of electromagnetic radiation defined by wavelengths that fall in the small band of the spectrum from 380 – 780nm, between Ultraviolet and Infra-red radiation, to which the human eye is sensitive. As electromagnetic wavelengths get shorter, at 300nm or below in the UV range, the energy of the photon increases and can become very harmful to human beings, although this part of the electromagnetic spectrum is not picked up by the eye it can affect other parts of the body such as the skin (Taylor, 1994) (Gallagher, Hill, Bajdik, & Coldman, 1995). The physics of light and lighting design are well understood in connection to the human visual system and comprehensive guidance documents are available such as the *Society of Light and Lighting's Code for Lighting* (2012). It is important to understand what these terms show about our knowledge of the effects of light and the response of the human body, this section will give a brief overview of a few basic principles in the context of this thesis.

5.1.1 Luminous Flux and Luminous Intensity

Radiant flux describes the electromagnetic radiation emitted by a source and is measured in watts. In terms of light, radiant luminous flux is the unit used to measure the amount of light emitted by a source, measured in lumens. Luminous flux is radiant flux multiplied by the relative spectral sensitivity of the human visual system by wavelength. The sensitivity of the human visual system is normally described by the CIE Standard Photopic Observer or photopic

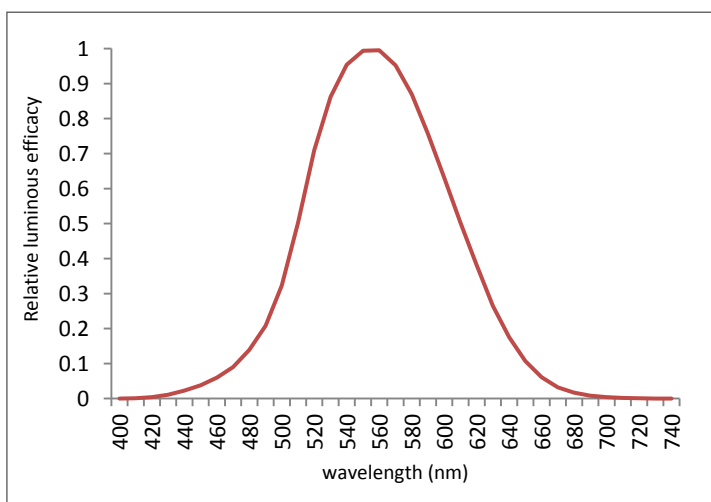


Figure 5.1: Human photopic luminous efficiency curve $V(\lambda)$ reproduced with data from International Commission of Illumination (CIE)

luminous efficacy curve $V(\lambda)$ shown in Figure 5.1. Luminous flux directly links light energy to the response of the human visual system identifying the vital link to humans and the need for light to perform visual tasks. It is also important to note that luminous flux is used

to describe the total light output of a light source in all directions.

Luminous intensity is luminous flux emitted in a given direction; it is described as the amount of light energy produced per unit solid angle in a specified direction and measured in candela.

As luminous flux specifically defines the response of the human visual system to light stimulus it is necessary to make a quantifiable connection between radiation flux and luminous flux in order that it can be evaluated in relation to other energy processes. As Boyce (2003) notes the International Commission on Illumination (CIE) determined that 1 Watt radiant flux at a wavelength of 555nm will produce 683 lumens, the constant lumens/watt value is therefore 683lm/w for the CIE Standard and Modified Photopic Observers. This in turn creates a direct link between radiometric and photometric quantities. This value is different for the CIE Standard Scotopic Observer, as it defines the response of the rod cells within the human retina. With peak sensitivity at 507nm the relative sensitivity of the scotopic system to light at 555nm is 0.402 therefore the constant is calculated as $683 \times 0.402 = 274 \text{ lm/W}$.

As mentioned above these values are relevant to understand the performance of the human visual system but if the non-visual system is shown to require light stimulus with different characteristics, such that the luminous efficacy curve is different to the photopic, this connection would not be relevant. These measures of light intensity are directly related to the spectral sensitivity of the human visual system therefore another way of measuring light intensity might need to be developed in order that a connection between the radiometric and the circadian systems can also be defined.

5.1.1.1 Luminance and illuminance

Luminance and illuminance are two common lighting measurements describing opposing effects of light. One is a measure of the light emitted from a source and the other is a measure of the light falling on a surface area. Luminance is luminous intensity, or the amount of light radiation emitted from a source in a given direction and is measured in candela per square metre, cd/m^2 . The luminance of a surface is also related to its perceived brightness. Illuminance is the luminous flux or amount of light falling on a unit area of a surface and is measured in lumens per square metre lm/m^2 given the unit lux. There is obviously a link between the amount of light falling on a surface and the amount of light reflected from the same surface.

Illuminance or Lux values are generally given in guidance for the design of lighting environments both internally and externally, such that a certain amount of light needs to be falling on a surface for a person to be able to perform a specific visual task. Table 5.1

reproduced from Society of Light & Lighting's Code for Lighting¹ (2012) which includes information taken from BS EN 12464-1 (2011), shows recommended lighting levels for a selection of visual tasks which are often performed within the built environment as guidance to the lighting designer. Previously provided by Illuminating Engineering Society's Code for Lighting or by the Chartered Institute of Building Services Engineers (CIBSE), since 2002 the British Standards Institute have taken on the Committee for European Standardisation's (CEN) recommendations for lighting levels in the United Kingdom. There are around 200 standards relating to lighting design which include BS 8206-2:2008 (2008) for daylighting and BS EN 12464-1 (2011) for lighting indoor work places. These standards specify quantitative lighting levels for a wide range of both internal and external spaces an example of which is shown in Table 5.1.

Table 5.1: Recommended lighting levels for a variety of visual tasks (reproduced from SLL Code of Lighting)

Type of area, task or activity	Lumens/m ² (lux)	Specific requirements
General areas within buildings		
Circulation areas and corridors	100	Illuminance at floor level
Bathrooms	200	
Entrance halls	100	
Offices		
Writing, typing, reading	500	
Technical drawing	750	
Educational buildings		
Classrooms	300	Lighting should be controllable
Art rooms	500	
Music rooms	300	
Teaching workshop	500	
Auditorium, lecture halls	500	Lighting should be controllable to accommodate various A/V needs
Healthcare premises		
Waiting rooms	200	
Corridors: during the day	100	
General ward lighting	100	Illuminance at floor level
Examination and treatment in ward areas	1000	Examination luminaire may be required
Industrial activities & crafts: ceramics, glassware		
Precision working e.g. hand painting	1000	
Manufacture of synthetic stones	1500	

¹ The Society of Light & Light (SLL) is part of the Chartered Institute of Building Services Engineers (CIBSE) which was preceded by the Lighting Division of CIBSE and the Illuminating Engineering Society (IES).

These lighting levels can range from 100lux for corridors and circulation spaces up to 1000lux for detailed or fine work such as colour inspection as part of a manufacturing process. The illuminated surface is also identified depending on the task as the light level will change between a horizontal plane at desk height to the horizontal surface of the floor as in some areas it is only necessary to consider the light that reaches the floor.

This guidance has been driven both by the response of the human eye to certain intensities of light and the boundaries of the eye's optimum performance as well as the efficacy of artificial light sources. As described in Chapter 2, the human visual system has the capacity to adapt to a wide range of light levels and is capable of performing a significant amount of tasks in low light levels as indicated by Figure 5.2.

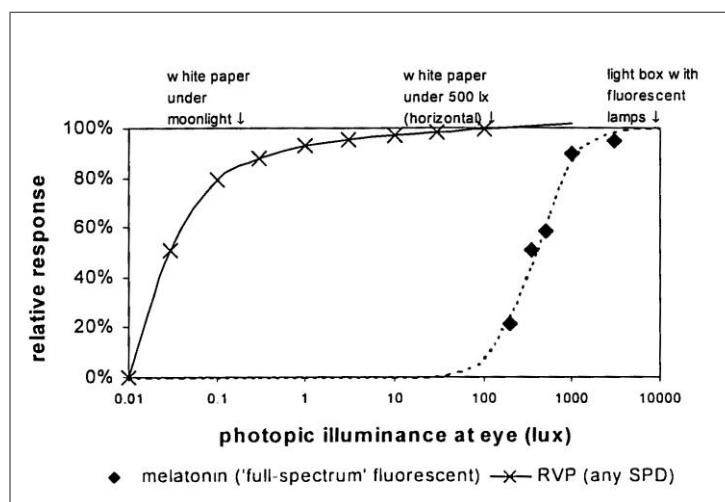


Figure 5.2: Performance of human visual system in a range of light levels taken from Rea et al (2002a)

The graph above shows the relative visual performance for high contrast reading materials as a function of illuminance at the eye where 0% represents minimum or threshold response and 100% represents maximum or saturated response. It is evident that the human visual system performs at very high relative response levels when illuminance at the eye is fairly low and reaches saturation point with an illuminance of 500lux when looking at a sheet of white paper on a horizontal surface, equating to approximately 100lux at the eye. This suggests that the human eye moves fairly quickly into photopic vision utilising the cone cells and the amount of light provided on the working plane is key to performance. As the same graph shows with data from a study by McIntyre et al (1989) superimposed on the visual performance by Rea et al (2002a) in their early study investigating circadian photobiology, the response of the human circadian system is potentially quite different. Minimum saturation or threshold of relative melatonin suppression (marker for stimulation of the circadian or non-visual system) is shown

not to occur until there is around 80-90lux at the eye. Saturation was not being achieved until 3,000-5,000lux was registered at the eye (based on the McIntyre data). Whether or not this data is now considered wholly accurate it does suggest that these two responses to illuminance levels are significantly different and they may require stimulation of different parts of the eye. If this is proven to be correct then different lighting guidance including recommended levels of light for these different systems would need to be provided for designers.

5.1.2 Horizontal vs. vertical illuminance

As highlighted above recommendations for lighting designers and architects are normally focused on levels of illuminance measured on the working plane which is typically horizontal. These values are important so that enough light is provided for building users to be able to perform visual tasks whether that is an office environment or a school or a residential environment. The working plane is usually assumed to be at desk or bench top height or defined as a particular height such as the floor. Although this measure of illuminance is important so as to provide the correct lighting for different visual tasks it may not be the most relevant for other requirements of the lighting environment such as the non-visual system defined in Chapter 4.

Guidance information such as Society of Light & Lighting's Code for Lighting (2012) has more recently acknowledged that there are other important aspects of the lighting environment which should be considered such as occupant satisfaction and appearance, defining suitable colour rendering indexes and colour temperature. There is an abundance of literature which provides valuable interpretation of the standards; however it is often the case that design decisions are driven by the quantitative lighting values. This is particularly the case when they are connected to a regulatory body such as the UK Building Regulations.

Taking into consideration the biomedical research described in Chapter 4 which provides a growing evidence base of the role light plays in a number of physiological processes within the human body it may be as relevant to consider the light received at the eye as a design parameter. This would require measuring light in the vertical plane or vertical illuminance and what is sometimes more specifically described as corneal illuminance. For example this illumination measure outlined by Aries et al (2003)(2004) does not currently feature in specific lighting guidance but is a more important measure for the impact of light on the human body. The early study by Rea et al (2002a) suggested that there was approximately an 80% reduction

in the illuminance value at the eye in comparison to the horizontal working plane, the difference between 500lux on the horizontal plane and 100lux at the eye, which represents a significant difference.

A recent study of a classroom environment by Bellia et al (2013) also showed that there was a substantial difference between the impact of light received at the eye and light received on the horizontal desk plane. Data collected during the study showed that this was the case throughout the majority of the day with a slight variation due to seat position in relation to the window location as well as light source. When considering an overcast day with supplementary electrical lighting, which could be described as a fairly typical scenario, there was a reduction from measured horizontal illuminance to illuminance at the eye of 30% to 55%. In comparison considering the same room just being lit by diffuse daylight from an overcast sky condition the difference between the two values ranged from +25% (illuminance at the eye was greater than on the horizontal plane) to -65% (illuminance at the eye was less than on the horizontal plane). In this lighting scenario there was a greater variation between the two values across the day, an effect of the changeable nature of daylight but illuminance values at the eye were generally low throughout the day and in particular in the from midday onwards. This study highlights the difference between the light that falls on a horizontal plane and the light that 'falls on' or reaches the eye of the occupant whether that light is provided by natural or artificial sources.

Predicting or assessing the amount of light that reaches an occupant's eye is not straight forward as it will be affected by more parameters than the light falling on a horizontal plane such as the position of the person's gaze which is also unlikely to be constant. However if the light reaching the retina is proven to be a key stimulus for human well being it will be as important for designers to consider illuminance within a space as much as horizontal illuminance. Until there are new guidelines for recommended lighting levels to maintain the physiological well being of the building occupant as well as their visual performance it will be necessary to make assumptions for appropriate light levels received at the eye based on the growing biomedical evidence base.

5.1.3 Correlated Colour Temperature

The measurements of luminous flux or luminance and illuminance quantify the amount of light energy provided but do not tell the designer anything about the appearance or quality of that light energy. For example the light provided by two different sources that have the same

luminance may look completely different in colour. The colour of light depends on a number of factors as described by Boyce (2003); spectral distribution of the light reaching the retina of the eye, the luminance of the source, the colour of the surroundings and the state of adaptation of the person observing the light.

Therefore the colour appearance of light is a complicated parameter to measure particularly as some of the factors are subjective. Although in this way coloured light does not really exist, as it is based to a certain degree on the perception of the individual, the International Commission on Illumination (CIE) have provided a quantitative measure for the colour of light from a given source. The CIE colorimetry system is a complex approach which is based on colour matching and through which three colour matching functions have been developed. These functions are not based on physiology but on mathematical models where any coloured light can be identified by two chromaticity coordinates.

Two more simple metrics using single numbers have been developed based on the CIE colorimetry system and are regularly used by the lighting industry; correlated colour temperature (CCT) and CIE General Colour Rendering Index (CRI). Correlated colour temperature (CCT) is a metric for the colour appearance of light emitted by a given light source and is closely connected to the CIE 1931 chromaticity diagram and more specifically the Planckian locus. The Planckian locus connects the chromaticity coordinates of black bodies at

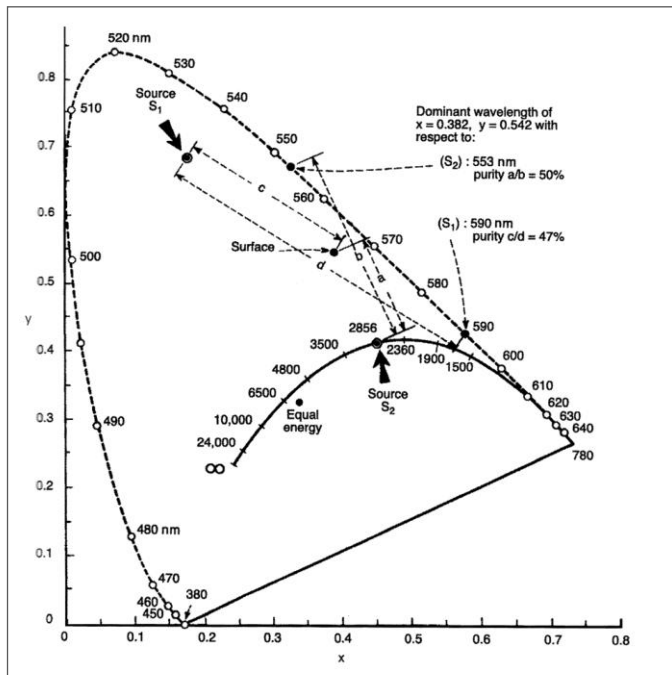


Figure 5.3: The CIE 1931 chromaticity diagram showing the spectrum locus and the Planckian locus (taken from Boyce (2003))

different temperatures and sits at the centre of the CIE 1931 chromaticity diagram shown in Figure 5.3.

As clearly described in Boyce (2003) the spectral emission of a black body is defined by Planck's law of radiation and is therefore a function of its temperature only. The appearance of those light sources whose chromaticity coordinates lie directly on the Planckian locus are described by the colour temperature. Those light sources

whose coordinates lie close to the Planckian locus but not on it are described by their correlated colour temperature which is defined by the iso-temperature line that is closest to the chromaticity coordinates, the line running across the Planckian locus at a particular temperature.

Although cultural associations have taught people that red and orange are warm colours, with the connotations of a warm fire for example and that blue and green are cold colours it is actually the opposite in terms of colour temperature. Blue light has the higher colour temperature at anything above 5000 K with yellow to red light having lower colour temperature between 2700-3000 K, this is because red light has a longer wavelength and is therefore the first colour to be emitted as heat increases. The correlated colour temperature metric is applicable to light sources that are technically white and will define the colour appearance of a range of light sources from incandescent at 2700K to fluorescent lamps up to 7500K. This metric only applies to those light sources whose chromaticity coordinates lay within the iso-temperature lines those; that lie above or below should not be given a correlated colour temperature as they will appear greenish or purplish respectively.

5.1.4 Spectral Power Distribution

The correlated colour temperature of a light source will give an indication of the area of the spectrum in which it produces the most energy as a factor in its colour appearance but it will not tell you the specific spectral power distribution (SPD) of the light the lamp produces. Daylight can be described as having a colour temperature of anything from 5000k-20000k. It is also sometimes described as 'full-spectrum' as it provides light energy across the visible spectrum but this does not necessarily mean it is a smooth and uniform distribution. It is difficult to truly compare an artificial light source with daylight due to its variable nature, however lighting manufacturers often market their lamps as providing 'full-spectrum' light or that they mimic daylight. When a lamp is given a colour temperature of around 5500k-6000k it is often assumed that the light provided is similar to that of daylight but the correlated colour temperature (CCT) of a light source will just give the black body temperature to which it is equivalent. This will not guarantee a similar distribution of energy across the visible spectrum.

The Lighting Research Center (LRC), New York undertook an investigation into some lamps that have been termed 'full spectrum' (Rea, Deng, & Wolsey, 2005). They showed that if you compared the spectral power distribution (SPD) of a lamp with a correlated colour

temperature (CCT) of 5500k that is described to be ‘full spectrum’ and a ‘full spectrum’ incandescent light with daylight at a similar CCT of 5500k the spectral distribution is markedly different, both from each other and from daylight. This can be seen clearly in the graph in Figure 5.4 taken from the study evaluation by Rea et al (2005) at the Lighting Research Center. The blue-shaded area indicates the part of the spectrum between 460-480nm that has been shown in biomedical research referenced in Chapter 4 to be most effective in stimulating non-visual or physiological response. It is clear that the relative power produced by both artificial lamps is significantly less than produced by daylight at this part of the spectrum.

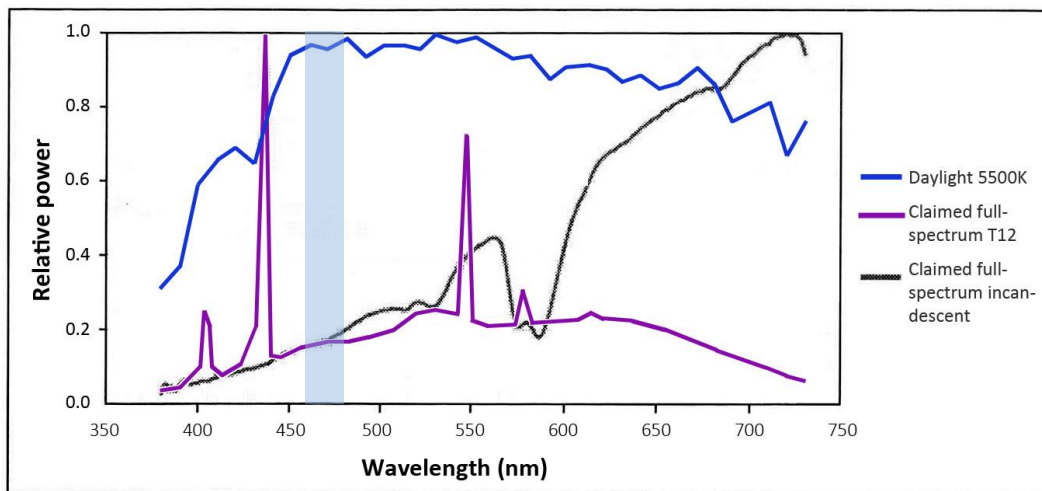


Figure 5.4: Spectral power distribution comparison between two ‘full-spectrum’ artificial light sources and daylight (LRC website)

Rea et al (2005) suggest that ‘full spectrum’ is not a technical term but a marketing term playing on the perception that natural light is better than artificial light. They showed that when two similar T12 fluorescent lamps were compared, one of which claims to be full spectrum, the SPD is virtually identical yet the price tag is significantly different, the ‘full spectrum’ lamp being almost 3 times the price. Neither of which have an SPD anywhere near that of truly full spectrum daylight

As daylight is so variable it is not possible to use it as a sufficient comparison of the SPD of artificial lamps so it is suggested that they are compared with an equal energy spectrum, which is full across the visible spectrum. LRC have also suggested that it is possible to determine how close to this ‘ideal’ light source each lamp is by using a new metric, the FSI (Full Spectrum Index). It is calculated using the SPD of a given light source to determine how much it differs from the equal energy source. Using this metric, daylight with a CCT of 5500k has an FSI of 0.35 and a 4100k T8 fluorescent has a FSI of 7.40. The test showed that with an arbitrary cut-off at FSI = 2.0, below which indicated a ‘full spectrum’ light, a mixture of the lamps tested

could be classed as 'full spectrum' such as xenon lamps, some ceramic metal halide lamps and some fluorescents T12 lamps whether they are marked full spectrum or not. This would also include daylight from 4000k-11000k.

This research shows that neither the suggested correlated colour temperature (CCT) of a light source nor the fact that the manufacturer marks the lamp as 'full spectrum' provides clear understanding of the spectral distribution of light from a given light source. The correlated colour temperature of a light source will therefore not tell you whether it provides energy at the parts of the visible spectrum important to the human circadian system as highlighted in Chapter 4. It is important to understand the individual spectral distribution of a light source that is being used to light an interior environment and the potential affect this has on the well being of the person observing the light as well as the perceived colour of the light. Although this thesis is focused on the availability and provision of daylight this is as relevant for the provision of artificial as natural light and it is important for designers to consider all sources of light received by the building occupant.

5.1.5 Summary

The physics of light and how this is employed to provide optimum lighting environments for the human visual system is well understood by the lighting industry but this means that the current system of photometry is therefore intrinsically focused on the sensitivity of the photopic and scotopic system. As more is understood about the human non-visual system and the presence of a non-rod, non-cone photoreceptor in the human retina this system of photometry may no longer provide the means to assess and design the optimum lighting environment. This significant development may have an impact not only on recommended lighting levels but on how light energy is quantified as well as how the spatial distribution of light is measured. The reliance of the visual system on illuminance at the working plane is not necessarily as relevant for the non-visual system. It is more relevant to establish the vertical illuminance or more specifically the light reaching the eye or corneal illuminance.

If the spectral sensitivities of the non-visual system are different, responding to a shorter wavelength of light, understanding the spectral power distribution of a light source will be more relevant. The current metrics of correlated colour temperature and colour rendering index, although describing the appearance of the light do not necessarily describe the exact distribution of energy it produces across the visible spectrum. If a designer wishes to support

the well being of the building occupant as well as their visual performance, understanding the spectral qualities as well as the intensity of light sources used will be important.

5.2 Artificial light

Although daylight is the focus of this thesis it is also important to consider how the eye responds to artificial light. Establishing how the quality and quantity of light provided by this source differs from daylight will offer a means to better understand how designers can utilise artificial light to supplement daylight.

Some lighting designers and architects have come to depend on artificial sources of light to provide the required lighting environments to allow building occupants to perform a variety of tasks, particularly in geographical locations with limited availability of daylight. A variety of types of artificial light source have been developed since Edison's first light bulb in 1879 that provide effective lighting environments for people to perform a vast array of visual tasks no matter the time of day or night. However they all have slightly different luminous efficacies as well as spectral power distributions determined by the process in which they are made and how they produce light energy in the visible spectrum.

Since the invention of the first incandescent light bulb with a carbon filament in 1881, incandescent lamps have been the most commonly used in a domestic environment with the 60 and 100 watt being most popular. Recent drives in legislation for a reduction in energy consumption and CO₂ emissions have meant that the incandescent light bulb has become increasingly unpopular due to its inherent energy inefficiency, producing large amounts of heat energy as well as light. Many manufacturers are beginning to reduce the production of incandescent light bulbs in favour of more efficient lamps such as compact fluorescent or LED. The incandescent bulb produces a very warm, yellow light with its spectral output not reaching a significant level until a mid-spectrum wavelength of 500nm and increasing in relative power output all the way through to 750nm.

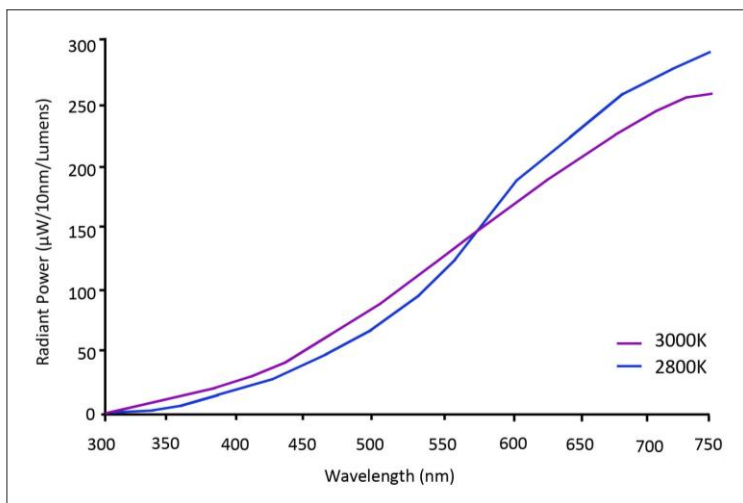
Although all these light sources give very different distributions across the visible spectrum, they all have a commonality by the fact that their spectral output, the energy that they emit across the visible spectrum generally peaks between 500-600nm. This part of the visible spectrum is the peak sensitivity of the human visual system described in Chapter 2. Unlike natural light which provides energy output across the full electromagnetic spectrum, some of these light sources may only produce light at key wavelength bands. It is in the interest of the lighting manufacturer to continue to make lights that produce maximum amounts of energy at the part of the spectrum most sensitive for the human visual system. As highlighted above the entire photometry system is defined by the photopic luminous efficiency function of the eye

including the equipment that is used to measure light levels within a space. As Rea (2002a) (2002b) notes all light meters are calibrated to spectral sensitivity of the L and M cones in the human fovea which make up 1-2% of the photoreceptors in the human retina.

The question that remains is whether or not artificial light sources which perform so successfully at one particular frequency range, often at the loss of the rest of the spectrum, respond to the other requirements of the lighting environment. Behling & Behling (2000) in their book on Sustainable Architecture note that even the most efficient light bulb requires more energy and produces more heat than light than the Sun for the same amount of light output. To get a better understanding of what they provide the next section will give a closer assessment of a range of artificial light sources. It will also examine to what extent they respond to the 460-480nm wavelength range highlighted in Chapter 4 as important for the non-visual requirements of the building occupant.

5.2.1 Incandescent lamps

Incandescence is heat driven light emissions and scientists discovered that if you pass electricity through a metal filament, often tungsten, the electrical energy is turned into heat energy which in turn produces light. By the nature of the process the light produced is perceived as a warm light in appearance as there is more energy emitted at the orange to red end of the visible spectrum and fairly little at shorter wavelengths, the blue end highlighted as more potent to the human non-visual system.



The spectrum produced by an incandescent lamp depends on the temperature of the filament and this can be adjusted by controlling the voltage running through the filament. A comparison of the spectral power distribution of two different incandescent lamps is shown in Figure 5.5.

Figure 5.5: Spectral power distribution of incandescent lamps reproduced from lighting manufacturer product information

In this way incandescent lamps are easily dimmable as

they work directly from the electricity supply and are compatible with an alternating or direct

current. Unfortunately this is a fairly inefficient process as only approximately 10% of the energy used by an incandescent light bulb is emitted as light with the rest being turned into heat energy, with luminous efficacy at approximately 12lm/W. A halogen lamp is essentially an incandescent lamp where halogen is present in the gas in which the tungsten filament is heated. The tungsten halogen lamp has a higher luminous efficacy of around 20lm/W and can be run at a higher luminous flux than a standard incandescent lamp.

The light is often perceived to be pleasant by building occupants. This might be because it produces a large amount of light at the part of the visible spectrum where the human visual system has peak sensitivity or related to a psychological connection between the orangey light and the warmth of a fire. However it does not produce much light at the shorter, blue end of the visible spectrum particularly within the 460-480nm range highlighted in Chapter 4 as important to stimulate human non-visual processes.

5.2.2 Discharge lamps

Gas discharge lamps, such as simple fluorescent and compact fluorescent lamps are used in a large number of industrial and commercial buildings and have a range of colour temperatures which provide different types of light. Discharge lamps create light by creating a discharge in a gas by passing electricity through it. These lights can be made to provide a specific wavelength range, whether a cool, blue light or a warmer yellow/red light is required. Each gas emits particular wavelengths of radiation depending on its atomic structure which in turn translates into a particular colour lamp.

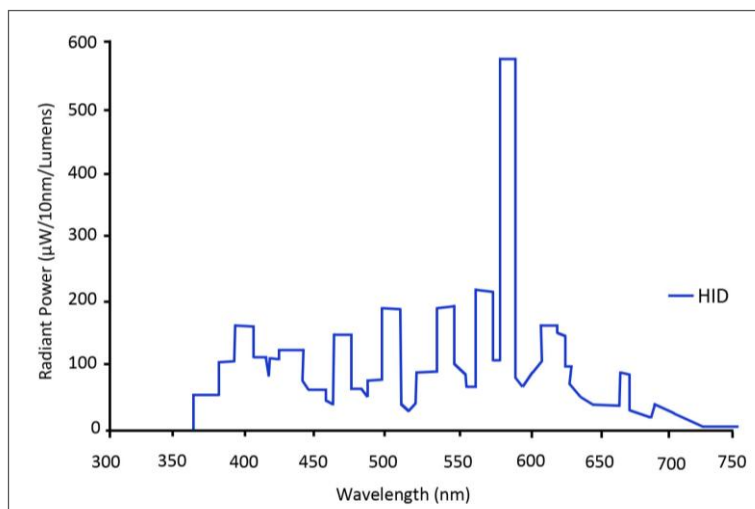


Figure 5.6: Spectral Power Distribution of discharge lamp reproduced from lighting manufacturer product information

Neon and argon lamps are also gas discharge lamps which produce red-orange and violet/pale lavender light respectively; neon lamps are often used for lighting external signs. Xenon emits a grey or blue-grey dim white light and also at high currents a very bright green-blue light. It is frequently used in xenon

flash lamps, xenon HID headlamps and xenon arc lamps. Sodium vapour (low pressure) emits a bright orange-yellow light and is widely used in sodium vapour lamps.

The spectral power distribution of a high-intensity discharge lamp (HID) is shown in Figure 5.6 above. HID lamps are more efficient than fluorescent lamps as more energy is converted into visible light, they therefore have a higher luminous efficacy. The choice of gases used in the HID lamp is determined by a number of factors; light intensity, correlated colour temperature, colour rendering index, energy efficiency and lifespan. As they often have a high luminous efficacy and light intensity they are often used where large internal areas need to be lit such as industrial buildings, stadiums and large public areas. Although the exact spectral distribution of light produced will depend on the choice of gases, as the SPD curve in Figure 5.6 shows, the light energy produced between 460-480nm can be significantly less than the warmer end of the spectrum.

5.2.2.1 Fluorescent lamps

The most commonly used gas-discharge lamp is a fluorescent lamp or tube. It uses electricity to excite mercury vapour. The mercury initially produces short-wavelength ultraviolet light which in turn causes a phosphor to fluoresce which produces light in the visible spectrum. The colour temperature of the lamp depends on the phosphorous material used on the surface of the tube. Halophosphate was often used but is now considered the old style of fluorescent coating and produces a less pleasant light due to the fact that it produces little green and red light. Although this light appears white to the eye it has an incomplete spectral distribution and therefore a low colour rendering index (CRI) rating. It is now more common to use a triphosphor coating which emits light more evenly across the spectrum and gives a more natural colour rendering to the human eye.

The spectrum of light emitted from a fluorescent lamp is a mixture of the light which is emitted from the mercury as well as the light emitted by the phosphorescent coating of the tube. A fluorescent lamp can emit light in peaks at different wavelengths across the visible spectrum unlike the constant distribution of an incandescent lamp. The spectral power distribution of a fluorescent lamp depends greatly on the chemical mix of the coatings therefore they can be manufactured to a chosen correlated colour temperature (CCT) by altering this mix of phosphors. Table 5.2 shows a range of typical fluorescent lamps and their different colour temperatures.

Table 5.2: Colour temperature and appearance of a range of fluorescent lamps

Colour temperature (Kelvin, K)	Colour description	Colour appearance
2700	Warm white	Orange
3000-3500	Neutral white	White
5000-6500	Cool white	Blue

As highlighted above and in section 5.1 the correlated colour temperature of a light source will provide some information about the colour appearance of the light as the different colour descriptions in Table 5.2 show. It will also provide some information about which parts of visible spectrum the lamp produces light energy but the CCT does not provide much more information about the complete spectral distribution of the light. Two fluorescent lamps with the same CCT could produce light with very different spectral power distributions with this type of lamp quite often producing a series of peaks at particular wavelengths. In this respect it is often difficult to know whether a fluorescent lamp will provide enough light energy at the part of the spectrum that has been identified as important to the non-visual system without knowing the specific spectral power distribution. The spectral power distribution of two different fluorescent lamps is shown in Figure 5.7.

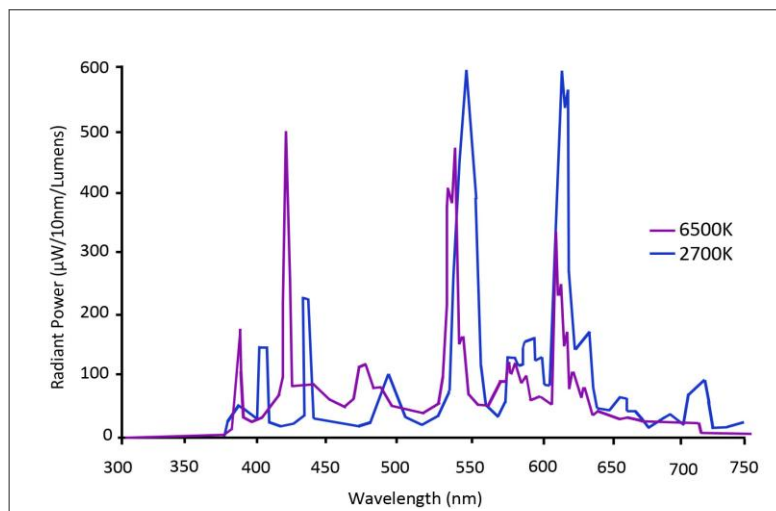


Figure 5.7: Spectral power distribution of different fluorescent lamps reproduced from lighting manufacturer product information

5.2.3 Light Emitting Diode (LED)

LED or light emitting diodes are a relatively new addition to the artificial lighting industry. The spectral distribution of the light produced depends on the materials used to make the semiconductor but is typically narrow band width. The luminance of light output from an LED is dependent on the current running through it and the temperature of the semiconductor; the higher the current input can be whilst keeping the temperature low, the greater the light

output. The luminous efficacy of the latest LEDs are quite good, typically between 20-30lm/W, and they can have a life expectancy of up to 100,000h depending on the material used to make them. The relative spectral distribution of Red, Green and Blue LEDs are shown in Figure 5.8 below. As LEDs can produce light within quite a specific and small range of wavelengths it is particularly evident that a number of LED light sources might not provided light in the 460-480nm range, with the exception of the blue LED.

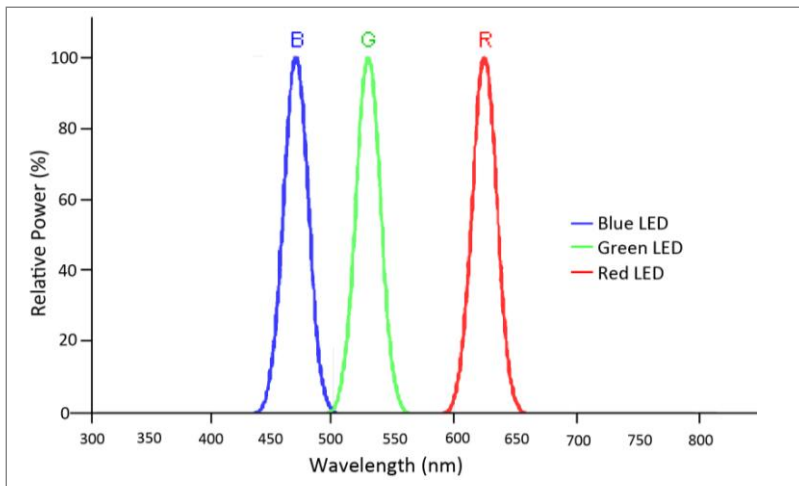


Figure 5.8: Relative spectral distribution of RGB LED reproduced from lighting manufacturer product information

Although it has been previously believed that because LEDs produce a very narrow bandwidth of light it militates against their use for general lighting, over the last few years a number of lighting manufacturers

have been using multiple LEDs in a single lamp. By

combining a red, green and blue LED they are able to produce any colour within the triangle formed on the CIE chromaticity diagram from one lamp. By combining this lamp with a lighting control the colour of the light produced can be changed gradually providing a 'dynamic' light. Other manufacturers have also incorporated a phosphor to the makeup of an LED lamp as a luminous layer. This process also produces a white light; the relative spectral distribution of

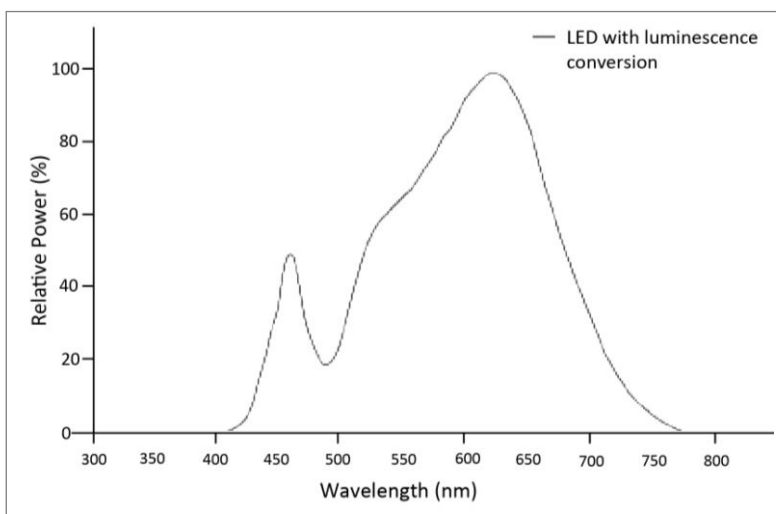


Figure 5.9: Relative spectral distribution of LED with luminescence conversion reproduced from lighting manufacturer product information

this type of lamp is shown in Figure 5.9. As Boyce (2003) highlighted 10 years ago it is evident that this is just the start and that LEDs will gradually become more common in general lighting systems, eventually taking the lion's share of the market.

These improvements to the spectral power distribution of the LED based lamps may provide more efficient lighting environments satisfying energy reduction requirements as well as user perception and visual performance. However, it is evident from Figure 5.9 that this type of white LEDs may not provide enough light between 460-480nm to satisfy the non-visual processes of the building user such as circadian well being. Although there is a shallow peak in the SPD curve at around 450nm it then drops off steeply before rising again around 600nm. As research and development continues the ability to provide very specific wavelengths of light as well as to incorporate these mono-wavelengths into other spectrally balanced lamps might start to address the requirements of both the circadian and the visual systems.

5.2.4 Summary

The overview of a range of artificial lamps above shows that each light source can provide a very different type of light based on how it was made and its overall efficacy. With the emphasis of the lighting industry currently focused towards the human visual system it is understandable that artificial lamps produced by manufacturers generally look to maximise light energy output around the part of the spectrum which is known to be most potent to the visual system. Current light level recommendations also address the sensitivities of the visual system the focus being on illuminance levels for specific tasks, however the importance of the spectral distribution of the light is often not fully appreciated by designers. Looking at the spectral power distribution graphs of the artificial light sources discussed above shows that none of these lamps produce much energy in the 460-480nm range which is suggested to be important for the non-visual system. This implies that higher overall lighting levels would be required from artificial lights to achieve the same impact as daylight on the non-visual system.

Although most architects acknowledge the value of natural light and the effect it can have on the perception and experience of a space most lighting strategies rely heavily on artificial light sources. This is particularly the case in northern hemisphere locations where a good quantity of natural light cannot always be relied upon. Providing the necessary light to support the requirements of the non-visual system and in turn the well being of the building occupant may not just be about providing the necessary intensity of light but providing light energy at the right wavelengths. Until an artificial light source is developed which more closely matches the spectral distribution of natural light a reliance on artificial sources to light interior spaces could be detrimental to the health and well being of the occupants. This will in turn require a better understanding of the natural resource of daylight to maximise its benefits whilst managing the fact that it is inherently difficult to predict.

5.3 Daylight

Humans evolved under light from the Sun therefore it is understandable that inherent biological systems are attuned to respond to the intensity and spectral quality of daylight. Artificial light sources have been manufactured to recreate light at wavelengths sensitive to the human visual system but they are currently unable to exactly mirror the qualities of daylight. Although daylight is a variable light source it is a readily available resource to which most humans have a positive psychological response as well as the inherent physiological response discussed in Chapter 4. Daylight produces light energy at all wavelengths across the visible and electromagnetic spectrum therefore it presents a potentially more valuable resource than artificial lamps to support human well-being.

The daylight that reaches the interior of a building and therefore available to support the well-being of the occupant is clearly dependent on the amount of light energy that is available at a given time and geographical location. In order to harness this natural resource, it is necessary to understand the factors that affect its variability. A variety of factors have an impact on daylight availability, such as global location, the season and time of day as well as local climate including cloud coverage and atmospheric conditions. A combination of these factors affects the intensity and duration of available daylight as well as having an effect on the spectral distribution of light that reaches any given building. The basic principles of these parameters will be outlined in the following sections in order to provide a basis for a more detailed discussion of their impact on design decisions and the data used in this thesis.

5.3.1 Solar Energy and Intensity of Light

Daylight is the light received as energy from the Sun and is a constantly changing source. Solar radiation falling on the Earth's surface can be divided into three components; direct light received from the Sun (sunlight), diffuse light from the sky vault after scattering and inter-reflection within the atmosphere as well as reflected diffuse light. The two latter components make up skylight. Sunlight and skylight together comprise daylight, providing light energy in the visible part of the spectrum as well as ultraviolet (UV) and infrared light.

The balance of sunlight and skylight at any time and place on the Earth's surface is a result of the Earth's atmosphere and the distance the light has to travel through it. For example, the greater the amount of water vapour and the longer the distance the light energy has to travel through it, the higher percentage of diffuse light in comparison to direct sunlight. This makes

the daylight received very specific to a given time and place which in turn makes it variable and hard to predict.

The light energy generated by the sun is at approximately 5,900K and is divided across the electromagnetic spectrum; 8% in the ultra-violet region, 48% in the infra-red and 44% in the visible spectrum. Outside the Earth's atmosphere the solar beam equates to 1400 W/m². Approximately a third of the light from the sun is reflected back into space with the rest being absorbed, warming the air as well as the Earth's surface. As the remaining light passes through the atmosphere it interacts with molecules of water vapour and pollution which causes reflection or scattering and therefore a percentage of this solar radiation arrives at the surface of the earth as diffuse light. Irradiance between 200-800 W/m² finally reaches the Earth's surface.

Atmospheric molecular scattering is dependent on wavelength with a greater percentage of the shorter wavelengths at the blue end of the spectrum being scattered causing the sky to have a blue colour, a process called Raleigh scattering. For example through a clear dry sky with the shorter wavelengths scattered, the longer wavelengths of light provide the appearance of the sun as a yellow orb of light.

5.3.2 Effect of solar altitude

Solar altitude, or vertical angle of the sun from the horizon, has the most impact on the intensity of available daylight; the higher the sun in the sky the greater the illuminance due to the shorter path of solar radiation to the given location. Solar altitude is affected by global location, specifically latitude or distance from the equator. As latitude decreases the solar altitude increases. It is also affected by time of day and time of year (unless on the equator) due to the Earth's rotation around the sun and therefore the intensity of daylight available changes throughout the day and dependent on the season.

5.3.2.1 Global Location

The changing nature of daylight is perceptible to most people, the essence of the desire to head to holiday destinations with more consistently blue skies and sunshine nearer the equator or the Southern hemisphere during cold Northern hemisphere winters. Considering the Earth's orbit around the sun as well as its own rotation on an angled axis it is clear that the available daylight is continually changing at a given point as well as varying depending on global location. The quantity and duration of daylight available depends heavily on the given location on the Earth's surface, for example there is a greater intensity of solar radiation in

locations closer to the equator than those in the Northern hemisphere. This can to a certain degree be offset by local climatic factors, for example, the fact that northern climates are much clearer offsets the reduction of horizontal beam illuminance with greater mid-summer clarity (CIBSE, 1999).

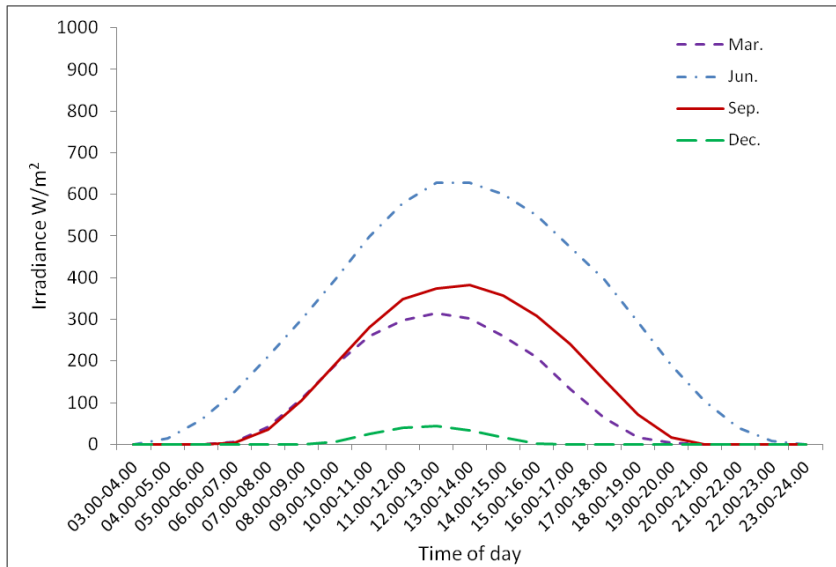


Figure 5.10: Graph showing monthly mean of hourly irradiance values for March, June, September and December for Helsinki, Finland extrapolated from SATELLIGHT

This difference in availability of daylight depending on global location is evident when looking at the annual average hourly global irradiance data for locations with different latitudes. For example, measured horizontal irradiance data for Helsinki, Finland at latitude of 60°10N shows the daylight availability changes significantly across the year as shown in Figure 5.10 above. Daylight availability varies from a daily period of 7 hours December to an average daily daylight period of 19 hours in the months of June.

In contrast, looking at measured horizontal irradiance data for Tangier, Morocco, at latitude 35°46N, shows less variability in the daily period of daylight availability across the year shown in Figure 5.11 below. The daily period of daylight ranges from 11 hours in December to 15 hours in June. The annual average of hourly values for horizontal global irradiance shows that the highest hourly value for Tangier is twice that of Helsinki. Although the daylight hours may balance out across the year the intensity of daylight is much greater in lower latitude locations, which offers advantages and disadvantages.

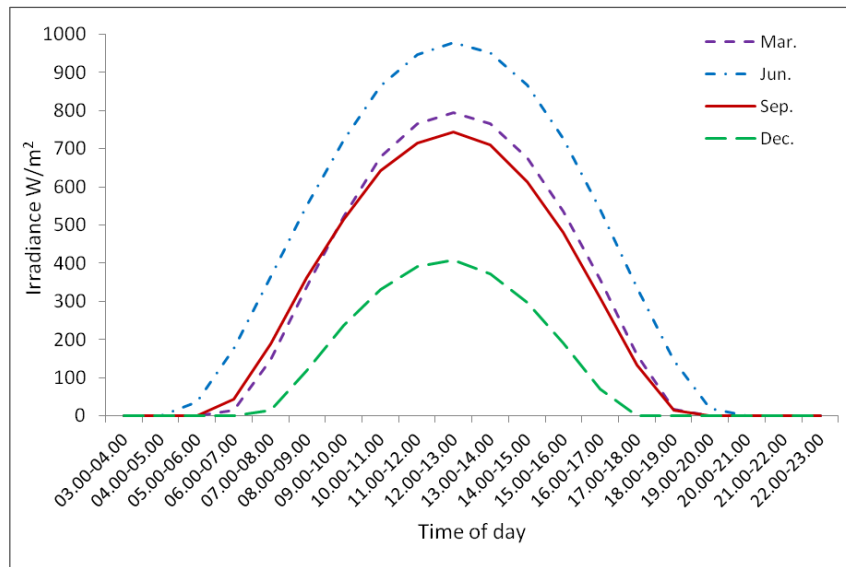


Figure 5.11: Graph showing monthly mean of hourly irradiance values for March, June, September and December for Tangier, Morocco extrapolated from SATELLIGHT

The availability of daylight in different locations ultimately impacts the amount of light that reaches a building interior. Understanding how this availability changes depending on different locations may have an effect on choice of building components used in a given location, in particular the glazing materials. Climate data for a particular location can also be averaged across each month of the year to be used for calculations requiring annual cumulative data which is a useful tool at the early stages of a building project or to establish potential heating and cooling loads.

5.3.2.2 Time of year/day

The Earth's annual orbit around the Sun changes the availability of daylight throughout the day and throughout the year. This connects daylight availability even further to a specific context. As described above, at places nearer the equator availability of external illuminance will be more consistent throughout the year than more northerly or southerly locations. The distance the light has to travel through the Earth's atmosphere will change during the day and during the year affecting the quantity of the light received at the Earth's surface.

Assessing external illuminance for a given location across the year creates a more accurate picture as to the variability which will be more extreme for some locations than others. In more northerly locations the position of the earth in respect of the sun due to the tilted axis means that there are a percentage of the winter months when there is very limited daylight availability. The measured horizontal irradiance data for Helsinki, Finland shown above in Figure 5.10 highlights that the intensity of solar energy varies significantly from winter to

summer months. In December the highest irradiance value is approximately 45 W/m^2 as a mean of the recorded light levels for this month. This light level increases in the summer months with the highest value stated at approximately 620 W/m^2 for the month of June.

The annual daylight availability may be balanced to a certain degree by the extended light availability during the summer months. The annual cumulative irradiance may therefore not seem too low as shown in Figure 5.12. However on a monthly basis there could be many days when the limited daylight availability would not provide enough light stimuli to maintain the human non-visual system. For example, in Helsinki during the winter months a minimum hourly value of 1 W/m^2 is recorded between 15.00-16.00hr in December as the mean of the monthly irradiance levels.

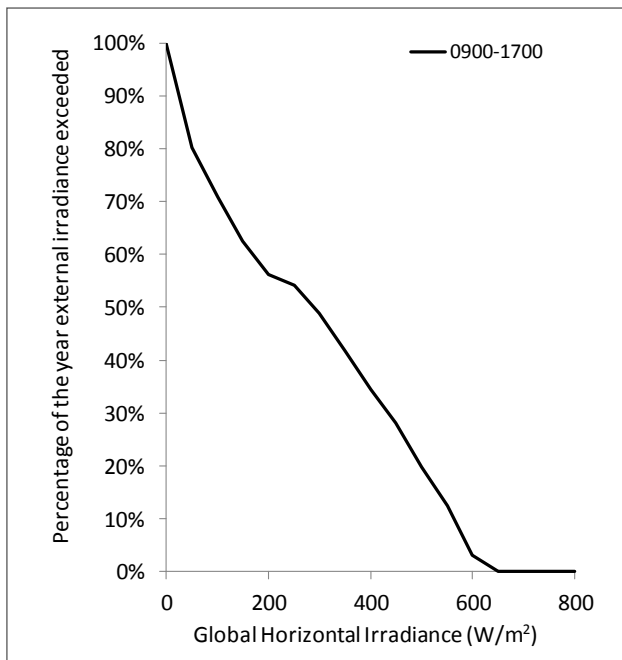


Figure 5.12: Percentage of the year that external irradiance exceeds a given level in Helsinki, Finland, data extrapolated from *SATELLIGHT*

In contrast the daylight availability at locations nearer the equator is much more consistent throughout the year. The position on the Earth's surface relative to the Sun is such that there is less of a variation in daylight availability throughout the year with the rotation of the Earth on its axis. The global horizontal data for Tangier, Morocco shows maximum hourly values for December and June of 410 W/m^2 and 980 W/m^2 respectively. There may be a reduction in intensity during the winter months when the Earth is furthest from the Sun but this has a limited impact. The intensity of light at these locations can become very intense during the summer months which can cause overheating from solar heat gain.

As well as the variability throughout the year, as the sun moves through the sky during the day both the quantity and quality of daylight changes. The variability of available daylight throughout the day increases as you move further away from the equator and the solar altitude decreases. Research outlined in Chapter 4 suggests that the non-visual system is more sensitive to the time that light is received than the visual system, for example, light stimulus to support circadian entrainment is most effective in the early morning. This emphasises the need to have a more detailed understanding of the changing daylight levels throughout the day. If a given location has low levels of external illuminance during certain parts of the day it will be necessary to make adjustments to the design of a building to maximise what is available. Taking into consideration global horizontal irradiance data for Helsinki, Finland, there are five months of the year when the irradiance levels do not get above 2 W/m^2 in the morning hours between 6 – 8am. For two months of the year irradiance levels do not get above 2 W/m^2 until after 9am.

5.3.3 The effect of atmospheric turbidity

The Earth's atmosphere is made up of a large number of gases which have an effect on the amount of solar radiation that reaches the Earth's surface. The various parts of the electromagnetic spectrum are affected differently by these gases depending on their wavelength, for example through a clear dry sky the shorter wavelengths are scattered more easily than the longer wavelengths. This also changes how we perceive the sky, the further the light from the sun has to travel the more scattering occurs therefore the lighter the sky becomes, for example, the sky at sea level would appear a much lighter blue with a sun that appears less intense.

Each gas within the atmosphere has its own spectral signature, a specific absorption/emission spectrum individual to its compound structure. There are three gases that specifically absorb visible and near Infrared radiation; H_2O (water), CO_2 (Carbon dioxide) and O_3 (Ozone or trioxygen) shown in Figure 5.13 below. However atmospheric gases are only responsible for absorbing a very small percentage of visible light so the majority of this part of the electromagnetic spectrum is redirected to the earth's surface.

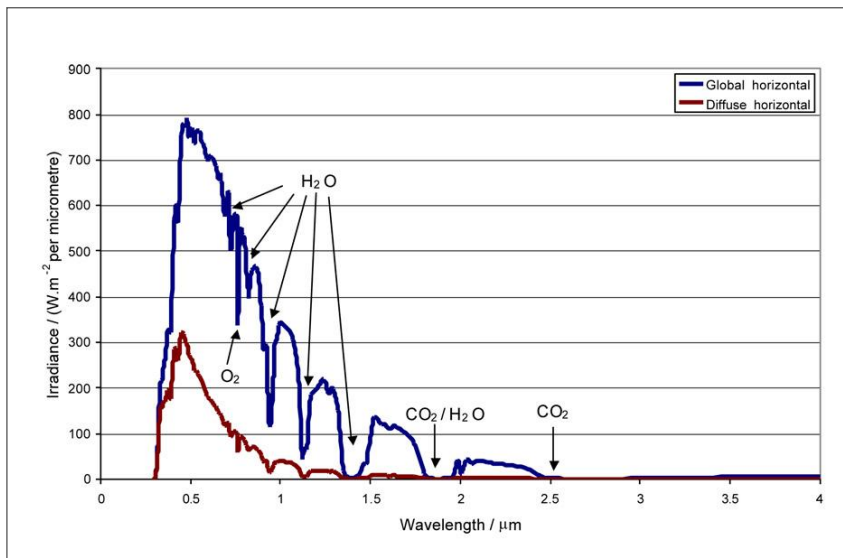


Figure 5.13: Spectral distribution of global irradiance and diffuse irradiance from a clear sky (reproduced from CIBSE Guide J)

The amount of moisture and pollution within the Earth's atmosphere increases or decreases the scattering and absorption of the solar radiation that occurs, altering the intensity of sunlight. This is described by the turbidity of the atmosphere which varies from mountainous to low lying areas and in relation to the level of pollution discharged into the atmosphere. As clearly outlined in Tregenza & Wilson (2011) illuminance turbidity, T_{il} , describes specifically the affect on visible solar radiation or illuminance levels at a particular location, for example dry conditions in high mountains would have illuminance turbidity equal to 1.5 whereas an urban location could be 3.5 and a heavily polluted industrial area could be 5.0. With an illuminance turbidity of 5.0 the reduction of solar illuminance would be equivalent to a path through the atmosphere which was five times as long as that through a clear dry atmosphere.

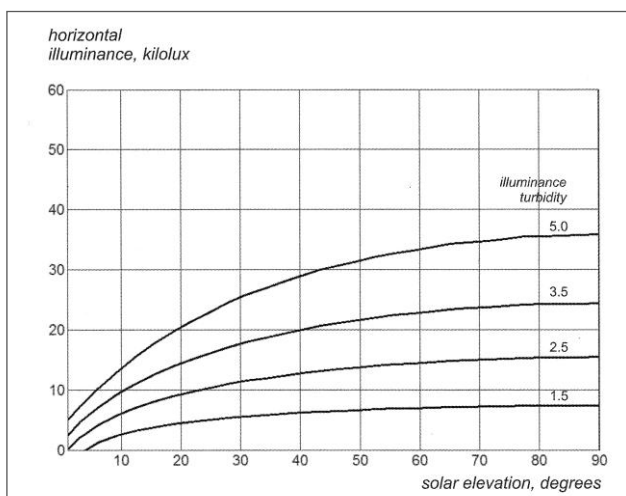


Figure 5.14: Graphs showing horizontal illuminance for clear sky alone and different levels of turbidity taken from Tregenza & Wilson (2011)

Due to the effect of scattering, direct solar illuminance is reduced as turbidity increases but the horizontal illuminance from a clear sky increases if taken into consideration without the Sun. The greater amount of moisture and pollution within the atmosphere the more scattering of the solar beam occurs, reducing the direct solar radiation reaching the Earth's surface but increasing the amount of reflected

or indirect light. Illuminance turbidity affects the intensity of light reaching the Earth's surface, altering the balance between direct and diffuse light received. It will also have an effect on the spectral distribution of this light potentially reducing the amount of energy in the middle to long wavelength range as more of the solar beam is scattered. Tregenza & Wilson (2011) provide a clear graphical description of the impact of turbidity on horizontal illuminance shown in Figure 5.14.

Global and local contexts and therefore the relationship with illuminance turbidity have an effect on the available daylight for any given location. The daylight availability for rural locations may differ to those in densely urban or industrial areas at the same latitude as these factors can influence illuminance turbidity. This emphasises the need to take into consideration the specific location of a building in the early stages of design.

5.3.4 The effect of cloud cover

Clouds are made up of millions of water molecules either as droplets or ice crystals gathered together and they absorb and reflect or scatter light from the Sun. Water molecules are excited by certain wavelengths of radiation, tending to absorb selected areas of the spectrum but generally leaving a balanced distribution across the spectrum intact. Water vapour is responsible for around 70% of the absorption of sunlight but mainly in the infrared range particularly at 2500, 1950 and 1450nm as well as at wavelengths nearer the visible spectrum at 930, 920 and 730nm. In general clouds do not absorb a large percentage of wavelengths from the visible spectrum and therefore do not have a significant impact on quantity of light reaching the Earth's surface.

There is a more significant impact of scattering by clouds, gradually reducing the intensity of light from the direct solar beam the deeper it travels into the cloud. The further the light has to travel through cloud the greater the reduction in intensity and the reason the base of a cloud sometimes appears darker. Clouds also produce a stronger scattering across the whole spectrum adjusting the balance of daylight towards a more diffuse than direct light component. This more uniform scatter across the visible spectrum rather than just at the blue end gives the sky a whiter appearance.

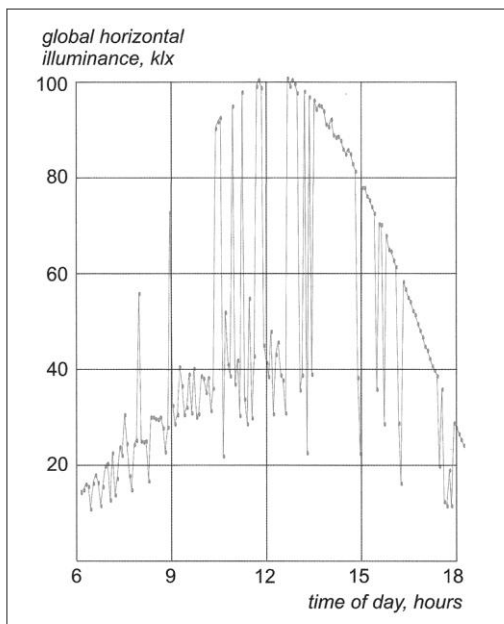


Figure 5.15: Graph showing the global horizontal illuminance for a summer day in UK taken from Tregenza & Wilson (2011)

The percentage cloud cover and density is extremely changeable in almost all global locations influenced by local climate and weather patterns or significant land mass such as mountain ranges. This means that diffuse daylight provided by overcast skies is very difficult to predict as it can change on an hourly basis. Diffuse horizontal illuminance data collected from a given location at a point in time will provide instantaneous information about the light level but may not provide the means to accurately predict the

illuminance data for the next day, the next week or even later that day. This variability due to cloud cover is clearly shown by Figure 5.15 of a

Summer day in UK where there is broken cloud cover in the morning making the global illuminance quite variable and clearing in the early afternoon which provides a much smoother curve of illuminance levels gradually decreasing through the afternoon.

This uncertainty of illuminance provided by an overcast sky has meant that annual cumulative illuminance data are often used which defines the percentage of the year for which a particular illuminance is exceeded. An example of this for two locations in UK is shown in Figure 5.16.

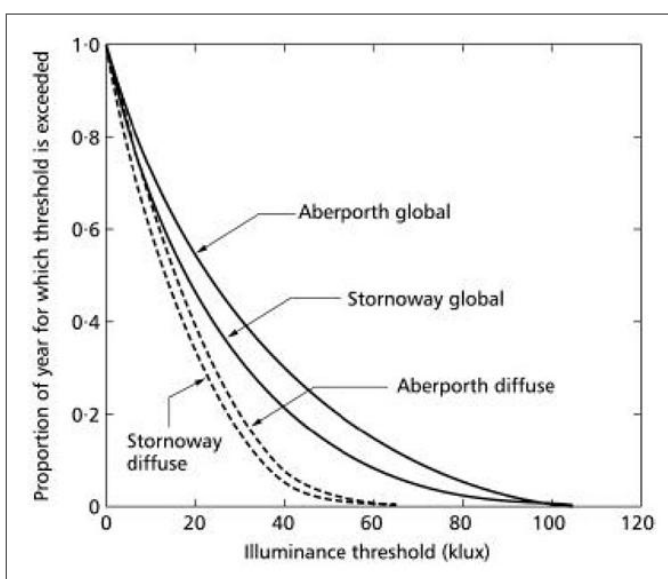


Figure 5.16: Annual cumulative illuminance graphs for locations in UK taken from CIBSE Guide J

This data can be calibrated in reference to particular scenarios such as different lengths of the working day or the school year excluding holidays, providing useful information for designers in terms of reliability of daylighting strategies.

The available daylight is therefore dependant on both the moisture and pollution within the Earth's atmosphere and more significantly by the cloud cover. This makes it difficult to accurately predict the external illuminance at any given time or location. By looking at illuminance data collected for a range of locations around the world it is possible to take into consideration this variability to a certain extent and make some assumptions as to the sky conditions.

5.3.5 Spectral Power Distribution of Daylight

The variability of daylight that reaches the Earth's surface does not just reflect the intensity or quantity but also the distribution across the visible spectrum. Almost all radiation-dependent processes are spectrally sensitive, whether that is photosynthesis by plants or the conversion of sunlight to Vitamin D within the skin of the human body. The spectral distribution of daylight is generally considered to be fairly evenly balanced at least across the visible range but there is still variability consistent with some of the parameters discussed above such as atmospheric conditions and cloud cover.

Although research to establish the spectral energy distribution of sunlight begun around the turn of the 20th Century research into the spectral make-up of daylight only really began in 1960s (Henderson & Hodgkiss, 1963) (Condit & Grum, 1964) (Judd, MacAdam, & Wysecki, 1964). Taking measurements of the spectral energy distributions of daylight these studies showed that the spectral distribution of daylight was most significantly affected by solar altitude and atmospheric conditions (Condit & Grum, 1964).

The local microclimate as well as related changes depending on season can have an effect on atmospheric conditions of a given location. Based on research into the spectral energy distribution of daylight this would suggest that the available daylight resource would change throughout the year as well as throughout a given day (Condit & Grum, 1964). Condit & Grum showed there was a reduction in the blue end of the visible spectrum relative to the yellow (560nm) with a hazy sky hazy but that as light clouds develop the blue component increases. Spectral distribution of an overcast sky is therefore different to that of a clear sky with more light across the middle to long wavelength range. This was also shown in an analysis of the lighting in an educational environment by Bellia (2013). The spectral distribution from an

overcast sky taken at multiple points in the morning and in the afternoon showed there was very little change throughout the day whereas data recorded under a clear sky showed more variability across the afternoon. The overcast sky may not vary as much as a clear sky due to the uniform nature of scattering across the visible spectrum.

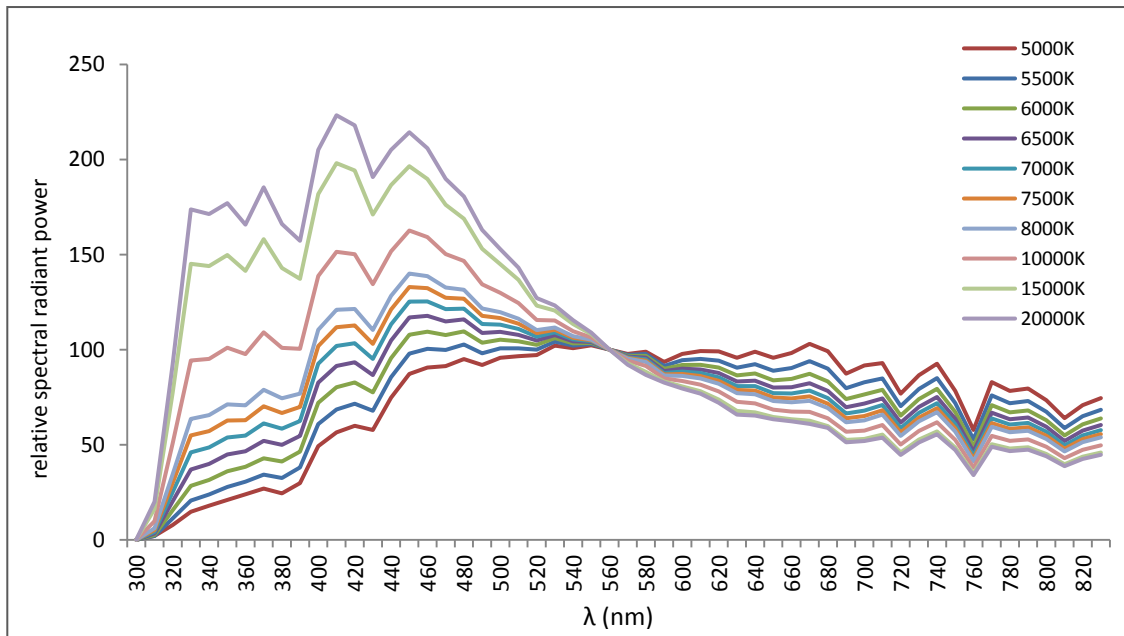


Figure 5.17: Relative spectral radiant power distribution of different daylight conditions derived from the CIE method of calculating daylight illuminants for colorimetry (taken from Wyszecki and Stiles

Measurements of relative spectral radiant power distributions of daylight by a number of researchers (Henderson & Hodgkiss, 1963) (Condit & Grum, 1964) identified that it was possible to determine chromaticity coordinates for different daylight conditions which were found to correlate well with those determined visually (Judd, MacAdam, & Wysecki, 1964). Typical daylight conditions can be expressed as correlated colour temperatures (CCT) ranging from 4,000K to 25,000K for a clear blue sky which suggests that the colour and therefore the spectral distribution of light of the sky conditions varies. However sky conditions are never static and their continuous change throughout the day will change the spectral distribution. Therefore these static conditions will only provide a basis to make assumed predictions of the potential quality of daylight.

5.3.6 Summary

As outlined above daylight has an enormous amount of variability, changing in connection to the time of day, the time of year and location from which it is perceived. This inherently variable nature is one of its most powerful qualities but also makes it difficult to provide a precise assessment of its ability to deliver the required lighting environment for an internal space. Understanding how this availability changes depending on different locations will have an impact on choice of building components specified, in particular the glazing materials.

Based on annual cumulative data, the variation across the year is balanced out to a certain degree but with reference to the non-visual which is sensitive to light at certain times of day, it is important to assess the daylight availability in more detail. The atmospheric conditions as well as local climate and specifically cloud cover play a part in the availability of daylight highlighting the need to understand the context of a building in more detail. The influence of these factors further highlights the complexity of predicting and designing for daylight.

This section has also highlighted that the parameters that influence the quantity of daylight available also affect the spectral quality of the light. The biomedical research discussed in Chapter 4 highlights the connection between light and non-visual processes and the sensitivity to specific parts of the visible spectrum distinct from the visual system. This suggests that the spectral distribution of light within building interiors is potentially important alongside the quantity of light. The sky conditions as well as the time of day can have an impact on this particularly at the blue end of the visible spectrum. This could play a part in the provision of light stimulus for the non-visual system particularly in locations where the intensity of light can be low during certain times of the year.

5.4 Predicting daylight availability

The design of buildings to best utilise daylight is dependent on understanding the parameters that affect the quantity and quality of daylight available at a specific location and time, a general overview of these basic principles were given above. If particular characteristics of light are important to stimulate the non-visual system and in turn well being then it is important to know what is available at a specific location from daylight. As soon as a building is placed within a context there are a series of more detailed considerations for the daylighting design of the internal spaces if it is to provide the necessary requirements for occupant well being.

It is evident that design decisions relating to the building form and external envelope will have an effect on the level of illumination received within internal spaces. The window is the threshold between outside and inside and dictates the lighting environment within the building. Various studies have highlighted how the size and position of window openings within a building facade influence the penetration of daylight into a building (Rennie & Parand, 1998) but without knowing what is available at a given location it is difficult to truly harness. This is even more relevant when considering the further physiological or non-visual effects of light on the human body due to the fact that lighting metrics do not currently take account of the requirements of these other processes. If daylight is to provide an internal lighting environment to support both the non-visual system as well as the visual system it is of greater importance to establish more information about the intensity as well as the spectral distribution of light.

In order to make accurate decisions during the design of a new building and in particular for the external facades it is necessary to have more detailed information about the available daylight at a given location. For a designer to understand the implications of certain design decisions relating to both form and specification of facade components it is also important for them to know how much of this available light reaches the external surface of the facade or more specifically the window system.

5.4.1 Climate-based daylight modelling

Due to the variable nature of daylight and the requirement for more accurate information about both intensity and spectral distribution a new approach to the modelling of daylight

design has been developed over the last decade. Climate-based daylight modelling (CBDM)² defines a new approach to daylight design based on measured data providing predictions of daylight availability in absolute quantities such as illuminance dependent on location and building orientation. In an evaluation report of CBDM for CIE Division 3 (Mardaljevic, 2008) it was proposed that the dynamic daylighting analysis provided by climate-based modelling offers a more realistic tool for daylighting designers than the Daylight Factor (DF) calculation.

A number of pieces of software have been developed which are capable of performing climate-based daylight simulation, most based on *Radiance*³, whether that is a specifically in-house created tool or end-user software such as DAYSIM. By utilising datasets from standard meteorological files such as provided by Chartered Institute of Building Services Engineers (CIBSE)⁴, US Department of Energy⁵ or the European Database of Daylight and Solar Radiation⁶ the variability in daylight availability dependent on location is inherent in the evaluation.

As the modelling is dynamic utilising datasets from real measurements which are often provided at hourly increments as well as incorporating illumination from clear skies both with and without sunlight, it is necessary to evaluate against a new daylight metric. A few metrics have been developed such as Daylight Autonomy and Useful Daylight Illumination (UDI). These metrics define the parameters of required daylight availability within a space such that an evaluation can be undertaken to establish the percentage of a room interior that achieves a certain level of daylight based on different lighting recommendations.

This method allows decisions to be made using accurate data, therefore improving the utilisation of daylight availability and potentially reducing over design and dependence on artificial systems. Although there has not been universal agreement of the most appropriate method in order that it can be incorporated into all international lighting standards the value in using this method has been acknowledged by some organisations; a description of the method is included in British Standard Code of Practice for Daylighting (BS 8206-2:2008, 2008)

² Climate-based daylight modelling (CBDM) was first used as a term by John Mardaljevic as the title of a paper given at National CIBSE conference, 2006.

³ Radiance is a computer software programme used for visualisation and analysis of lighting design developed by the Building Technologies Program at Lawrence Berkeley National Laboratory, California. <http://www.radiance-online.org/>

⁴ <http://www.cibse.org>

⁵ http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

⁶ <http://www.satel-light.com/indexgS.htm>

as well as credits being awarded for use of climate based analysis as part of a LEED (Leadership in Energy and Environmental Design) assessment⁷.

Although this thesis does not include the use of climate based modelling, the need to base the specification of building components on more accurate data is acknowledged. This thesis will use external illuminance data derived from climate data for a range of locations as part of the study of the effect of glazing on daylight distribution within building interiors.

5.4.2 Real data for Daylight and Solar Radiation

Real data used for the daylight as well as solar energy calculations are collected in a number of ways, most commonly from ground measurements taken at one of the weather stations set up in a number of countries around the world. The range and accuracy of information available will depend on the status of the weather station and the equipment they have at their disposal. Daylight and solar radiation information can also be collected from above using satellites to take images of the reflected radiation at the Earth's surface from which it is possible to derive other required datasets.

5.4.2.1 Ground measurements

Meteorological stations across the world collect a wide range of time series as well as cumulative weather data relating to local climate and sky conditions annually. This often includes solar radiation and daylight data which for a long time has been used to support the accurate modelling of heating and cooling systems within buildings. There are a number of private meteorological stations as well as public funded stations collecting data that is available to all via the internet. For example the US Department of Energy provides access to a comprehensive dataset from across the continent via the EnergyPlus website and the Chartered Institute of Building Services Engineers has collated datasets for 14 sites across the UK.

The International Daylight Measurement Programme (IDMP) set up in 1991 by the International Commission on Illumination (CIE) has collected daylight and solar radiation measurements at 48 stations in 22 countries across the world (4 of which have now closed). Each station is managed by an individual research team collecting data to support their own research but data are also shared across the programme. The types of data collected depends

⁷ Leadership in Energy and Environmental Design (LEED) is a rating system for the design, construction and operation of buildings launched by the US Green Building Council in 1998.

on the status of the station, a basic class IDMP station records at a minimum global horizontal illuminance, diffuse horizontal illuminance, global horizontal irradiance and diffuse horizontal irradiance. Only the research class stations record zenith illuminance and global vertical illuminance in the four cardinal directions.

Although there are a larger number of stations now than there were 20 years ago they still only cover a fraction of the Earth's surface. By the fact they have to be fixed locations and can often be over 100km apart even in countries where there are a reasonable number of stations means that the data they provide can have limitations. The distances between sites can be problematic for some data requirements and there are still a significant number of areas where no data are being collected such as outside Europe and North America.

5.4.2.2 Satellite measurements

Another method which overcomes some of the limitations of collecting measurements from the ground is by computing radiation data from satellite images taken of the Earth's surface. Satellites offer a good source of data as they provide extensive and regular measurements of the Earth's atmosphere, the challenge being how to accurately derive precise radiation values at the ground level. Cano et al (1986) outline two types of method for estimating the global radiation at ground level from satellites; a statistical approach based on the relations between ground and satellite data or a physical approach using radiative transfer models to formulate a relationship between ground and satellite.

Cano et al (1986) developed a statistical method for the determination of the global solar radiation from meteorological satellite data which has since been used as the basis for the determination of solar radiation and daylight information by a number of organisations. Their approach has two steps and ultimately relies on a training set of data collected from ground measurements to determine the parameters of the model which in turn predicts the global radiation. The first step is to establish a cloud cover index for each location or pixel of the original satellite image which is achieved by creating a reference map of albedo (reflectance) values for clear sky conditions. The cloud cover index is then derived from the comparison of the current satellite image and reference albedo map. The actual atmospheric transmission factors are computed using pyranometric data measured on the ground and a statistical regression is undertaken between these factors and the cloud cover index at the same locations. From this a global radiation map can be computed for the given area.

The most challenging part of this approach is the need to determine the presence of cloud and whether the radiation detected by the satellite image is from the ground or from cloud cover. This is resolved in the method developed by Cano et al (1986) by the fact that the cloud albedo is higher than the majority of ground conditions with the exception of snow. Therefore the reference albedo has the minimum value which in turn allows the detection of the presence of clouds in satellite image by a higher albedo value resulting in a higher irradiance recorded.

5.4.2.3 Daylight and solar radiation data collected by SATELLIGHT

The *SATELLIGHT* (SATELLIGHT, 1997) initiative was set up to provide daylight and solar radiation data for exact locations across Europe collecting data for a period of 5 years. Researchers had previously relied on estimated data based on a small number of measurement stations which covered a limited area. *SATELLIGHT* uses images taken from Meteosat type geostationary satellites located above the equator at an altitude of 36,000km from where it can see one half of the Earth's surface, an example of which is shown in Figure 5.18.

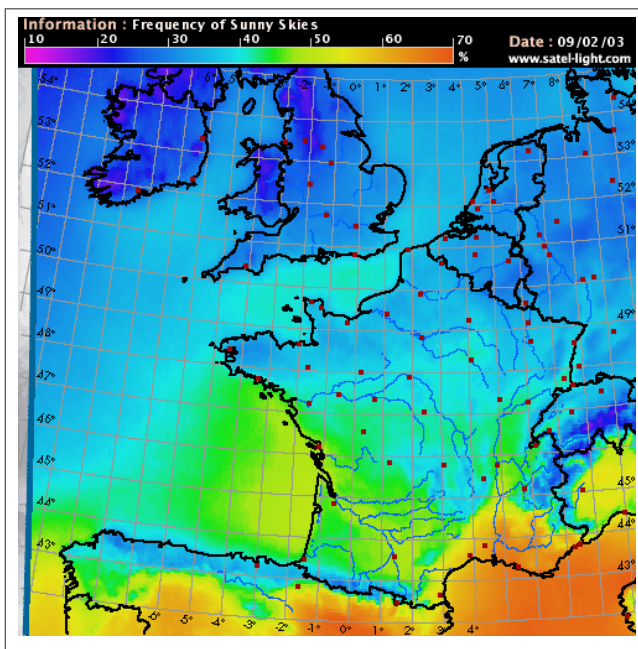


Figure 5.18: Image of data taken from Meteosat satellite of the frequency of sunny skies across a full year taken from *SATELLIGHT*

From the images, reflected radiation is measured in three spectral bands; visible 0.5-0.9 μ m, water vapour 5.7-7.1 μ m and IR 10.5-12.5 μ m. Each pixel of the image covers a specific area of the Earth's surface from South to North poles, the area covered by a pixel ranges from approximately 5km in longitude by 6km in latitude in North Africa (34°N) to approximately 5km in longitude by 16km in latitude over Scandinavia (64°N). The image

scan is repeated every 30mins. Global horizontal irradiance is the only parameter provided directly from the satellite image and is estimated using

the Heliosat method proposed by Cano et al (1986) and further developed by Beyer et al (1996). All other solar radiation and daylight information such as direct and diffuse horizontal

irradiance as well as global and diffuse horizontal illuminance is computed from this data using mathematical models.

Making accurate predictions as to the amount of daylight received within a building interior is always going to prove difficult due to the continuously changeable nature of daylight. Using monthly mean of hourly values collated over a number of years provides a more detailed picture of the potential daylight availability at a given location. Although this may still not capture the true instantaneous nature of daylight it does provide a clearer picture than using an approximated calculation such as the average daylight factor based on one assumed sky condition unlikely to be appropriate for many locations. As well as providing hourly irradiance data for any location in western and central Europe the *SATELLIGHT* programme derives illuminance data from the measured irradiance data using the Olseth (1989) luminous efficacy model. This model was chosen due to its ability to adapt to variations in the atmospheric conditions as well as to the depth of cloud (*SATELLIGHT*, 1997).

To look more closely at the differences between daylight availability at different latitudes and understand the impact this will ultimately have on the daylight received within the building interior this thesis includes daylight information from three locations at different latitudes within the Northern hemisphere provided by the *SATELLIGHT* programme: Helsinki, Paris and Tangier, specific locations shown in Table 5.3. These cities were chosen to provide a range of locations within the Northern hemisphere with varying distances from the equator from which it would be possible to ascertain the variability based on latitude. The variation in spectral distribution may not play a significant part in some latitudes but a reduced quantity of light available may result in a detrimental effect due to the transmission of certain glazing systems.

Table 5.3: Longitude and latitude of chosen Northern hemisphere locations

Location	Latitude	Longitude
Helsinki	60°10N	24°55E
Paris	48°52N	2°19E
Tangier	35°46N	5°48W

A summary of the validation of the accuracy of the data provided by the *SATELLIGHT* programme is given in Appendix B.

5.4.3 External Horizontal Illuminance

The instantaneous nature of daylight also makes even these real measurements an estimate when looking to predict the daylight received within a given interior space. In the absence of measured instantaneous illuminance data it is necessary to use predicted data, this is achieved by using luminous efficacy models which estimate illuminance from solar radiation data and atmospheric parameters.

5.4.3.1 Luminous efficacy

As described above solar radiation produces energy across the electromagnetic spectrum including in the Ultraviolet and Infrared ranges. Irradiance describes the total energy received at the Earth's surface and the complete spectral quantity from Sun and sky and is denoted in Watts/m². The visible part of the spectrum, those wavelengths that the human eye is sensitive to are distinguished from the rest of the electromagnetic spectrum and referred to as light. The amount of light falling on a given area is described as illuminance and denoted by lux or lumens/m².

The Earth's atmosphere alters the ratio of visible light to total radiation from the sun, as Muneer (2004) describes, the global luminous efficacy of daylight is expressed as a ratio of illuminance to irradiance and is defined by the integration of the whole spectrum across the photopic luminous sensitivity of the human eye denoted as $V(\lambda)$ (as defined by the CIE) and the solar spectral irradiance denoted as $I_G(\lambda)$. This is the same as the luminous efficacy of a lamp which describes its energy output in relation to the sensitivity of the visual system in relation to energy input. These luminous efficacy values provide the means by which illuminance provided by daylight can be determined from irradiance measurements.

The distribution of radiant energy across the electromagnetic spectrum, between the visible and the invisible defines the luminous efficacy of daylight and it depends on a number of factors such as the sky conditions, whether it's clear or overcast as well as solar altitude. A number of researchers have collected simultaneous measurements of illuminance and irradiance in a given location to determine the impact of these factors in order to develop standard templates. Muneer (2004) describes the work of a number of these researchers such as Pleijel (1954), Blackwell (1954) and Dogniaux (1960).

A large percentage of this initial research was carried out for individual sky types, such as an overcast sky providing luminous efficacy models for these conditions. As Muneer suggests it is more useful for the design of window systems to have luminous efficacies that can be used

under all sky conditions. A number of luminous efficacy models have been developed to address this issue such as the Littlefair model (1988) which incorporates weighting sky diffuse, ground reflected diffuse and beam luminous efficacies with cloud cover.

The Olseth model (1989) used by the *SATELLIGHT* programme is based on the photopic luminous efficiency curve defined by the CIE and spectral irradiances which are obtained by an interpolation between transmittance models for cloudless and completely cloud covered skies provided by others (Bird & Riordan, 1986) (Stephens, Ackerman, & Smith, 1984). There is also the Perez et al model (1990) which is considered to be the most sophisticated and incorporates a sky clearness rating and the solar zenith angle. The Perez et al model is derived from hourly data recorded at 10 locations in US as well as 3 Central European locations. Through evaluation by Muneer & Angus (1993) undertaken against measured data it was established that the Littlefair model tends to under estimate global illuminance and sometimes over estimates diffuse illuminance whereas the Perez et al model was found to perform well for both global and diffuse illuminance estimations.

In the absence of measured data it is agreed (Littlefair, 1988) (Muneer, 2004) that using a luminous efficacy model to generate illuminance data from measured irradiance values is a reliable method. The process of deriving illuminance from irradiance measures is also outlined in section B.2 of BS 8206-2:2008 Code for Practice for Daylighting (British Standards Institute, 2008). By their nature none of the luminous efficacy models can be completely universal therefore care must be taken to match the atmospheric conditions at the chosen location.

Irradiance data is collected at meteorological stations at various locations around the world but illuminance data is only collected at a very limited number of locations. For example the International Daylight Measurement Programme⁸ (IDMP) promotes the collection of measured irradiance data at various locations around the globe and in some locations illuminance data to support research. Standard climate data is also available from a number of web based data sets such as Chartered Institution of Building Services Engineers (CIBSE), the European Database of Daylight and Solar Radiation⁹ as well as from EnergyPlus¹⁰, provided by the US Department of Energy.

⁸ <http://idmp.entpe.fr/> International Daylight Measurement Programme set up in 1991 by the International Lighting Commission (CIE)

⁹ <http://www.satel-light.com/core.htm>

¹⁰ http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

5.4.3.2 Standard sky types

The brightness of the sky (or sky luminance) has an impact on the daylight availability within an internal space and is affected by a number of the factors discussed above. With a percentage of daylight coming from indirect or reflected light and part of that from the sky itself it is necessary to know the luminance distribution of the sky. On a clear day the solar radiation is only scattered by the Earth's atmosphere and is brightest around the sun and darkest opposite the azimuth of the sun. This brightness distribution is different on an overcast day when the sun is not visible due to various layers of cloud and maximum luminance occurs at the zenith and with the darkest point at the horizon.

The daylight that reaches the interior of a room within a building is affected by the brightness of the patch of sky that is visible from the room which is not necessarily the whole sky. Therefore to make an accurate calculation of daylight illuminance it is necessary to know the luminance distribution of the sky and the predicted luminance of that particular patch. In order to make these assumptions of sky luminance distribution requires real measurements to be taken. With the commencement of the International Daylight Measurement Project (IDMP) in 1991 provided the ability to make accurate calculations on internal illuminance based on real datasets as well as to categorise the many different daylight conditions around the world, described as the CIE General Sky. Mathematical formulae for 'standard skies' were developed such that it was possible to describe the variation in luminance across a given sky type with elevation and azimuth.

The CIE Standard Overcast sky was the first to be fully adopted which describes conditions in which the lowest consistent levels of daylight occur in temperate climates. As Pritchard (1987) describes, measurements of sky luminance under overcast conditions have shown that it is more accurate to assume that there is a fairly uniform luminance in the azimuth but that it varies across any vertical plane. CIE Standard Overcast Sky, used as a basis for the Average Daylight Factor calculation is most accurate for locations in Northern Europe to predict the illuminance provided by daylight assuming a consistent cloud cover. This standard sky denotes a sky where the luminance distribution only varies with elevation getting brighter as the height above the horizon increases. This sky is considered to be three times as bright at the zenith as at the horizon but with no variation in horizontal directions. An assumed average illuminance level is given for this standard overcast sky of 5,000lux. This is a conservative estimation of the potential light available from the sky vault and is often used in order that it is possible to establish the worst case scenario for the availability of daylight in a given building.

CIE Standard General Sky, a formula which could generate a number of different sky types including the Overcast and Clear sky distributions from different parameters, eventually replaced the previous standards. This model was then adopted by the International Organisation for Standards (ISO) in 2004 *BS ISO 15469:2004 Spatial distribution of daylight – CIE standard general sky*. In order to utilise the CIE Standard General Sky to predict sky luminance distribution the most appropriate sky model from the 15 standard skies has to be chosen. It is necessary to have knowledge of the measured luminance distributions in order to make this choice. This makes the application of the CIE General Sky model quite complex and a number of researchers have proposed methods for selecting the most appropriate sky model such as Alshaibani (2011) and Ferraro et al (2013) as well as how to apply it to a daylight calculation (Kittler & Darula, 2006).

5.4.4 Vertical vs. horizontal external illuminance

The light that reaches the external surface of a given window within the envelope of a building is affected by a number of factors; the latitude of a given location and solar altitude at a given time in this context, the reflectance of the ground surrounding the building facade, reflectance and interaction from surrounding buildings as well as the orientation of the facade itself.

As discussed above by utilising *SATELLIGHT* it is possible to generate global, diffuse and direct horizontal illuminance values from the real dataset for the chosen sample locations. This provides a picture of the quantity of light reaching the earth's surface, on the horizontal plane. The horizontal surface of the Earth receives light from the full sky vault, taking into consideration any potential impact from surrounding context. It seems an obvious statement but tilted surfaces receive less light than a horizontal surface, potentially most significantly for vertical surfaces. Research around the impact of the orientation of a facade on the available external illuminance has been undertaken by others (Li & Lam, 2000) and guidance is also included in British Standard for lighting design (British Standards Institute, 2008). To establish how much of the available external daylight reaches the interior of a given space it is necessary to derive the illuminance level on the vertical surface of the glazing system.

This calculation requires derivation of ground luminance, therefore treating the ground as a reflector. If illuminance values from ground measurements were being utilised then it would be necessary to establish the reflectance value for the ground around a building dependent on the dominant material or specific quality. This is typically less than 0.2 but a greater reflectance is sometimes seen in agricultural areas where a large amount of brightly coloured

crop is growing or when the ground is covered in snow. The British Standard 8206:2008 (2008) provides a reference table for approximate reflectance values for external materials. The illuminance data produced by *SATELLIGHT* is based on a ground reflectivity of 0.15 as a default setting with the option to adjust based on more detailed knowledge of the ground condition.

A vertical surface, 90° from horizontal such as a window within a building facade, as well as receiving reflected light from the ground, receives light directly from up to half the sky vault even though it does not receive light from the zenith. This therefore requires the sky luminance to be defined as the vertical surface is receiving light either direct or reflected from this sky and not just reflected from the ground. Predicted vertical illuminance is derived by the *SATELLIGHT* programme by transforming the observed horizontal diffuse/beam irradiance into slope irradiance using a slope algorithm taken from a model developed by Skartveit & Olseth (1986) as described in the paper by the same authors (Olseth & Skartveit, 1997). This algorithm assumes Lambertian ground reflectance where the surface's luminance is seen to be uniform in all directions as well as accounting for local horizon effects. The slope illuminance is then derived from the slope irradiance using the same Olseth luminous efficacy model (1989).

Taking into consideration illuminance datasets for Helsinki, Finland a comparison was made of the horizontal and vertical illuminance values. Using the diffuse horizontal and diffuse vertical illuminance values in order to remove the effect of the contribution from direct solar beam the monthly mean of hourly values of a surface 90° from horizontal and facing West were compared to the horizontal illuminance values, this is shown in Figure 5.19.

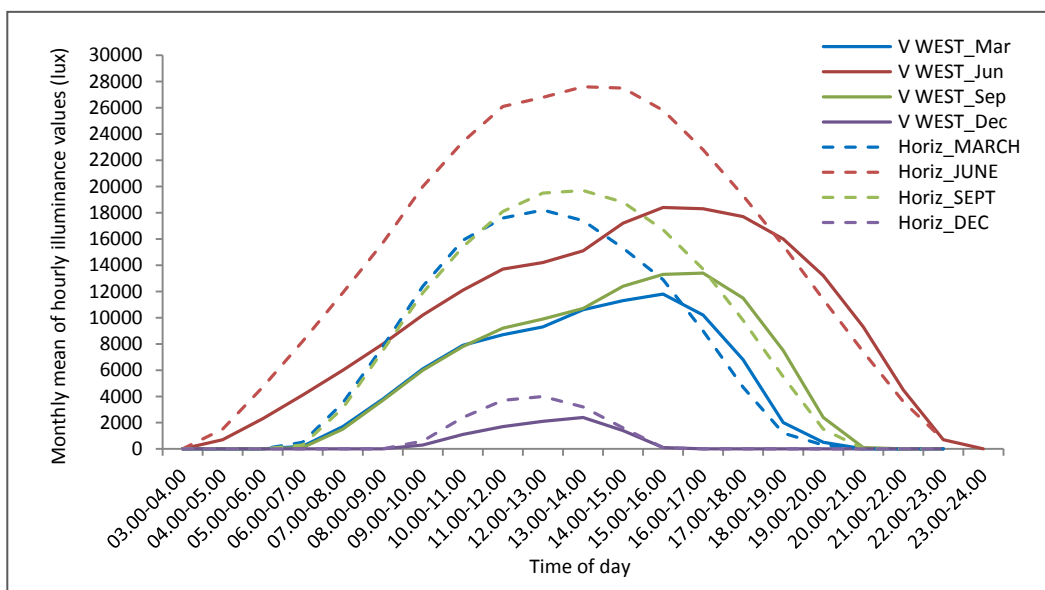


Figure 5.19: Graphs showing the diffuse horizontal and diffuse vertical illuminance values in Helsinki, Finland for March, June, Sept and Dec extrapolated from climate data from *SATELLIGHT*.

Looking at values for March, June, September and December this comparison showed that there was a reduction from horizontal illuminance to vertical illuminance of approximately 50% during the morning hours, with slightly less of a reduction from midday onwards. This is considered to be a result of the position of the sun in the afternoon hours providing increased diffuse light on the westerly facing vertical surface.

The implication of the difference between external horizontal illuminance and vertical illuminance means that each orientation of a given vertical surface will affect the daylight availability; incorporation of this parameter is one of the proposed improvements of climate-based modelling over the basic Daylight Factor method.

By comparing the global vertical illuminance at all four cardinal points for Helsinki the difference is as it might be expected with the monthly mean of hourly values. The South facing surface reports greater illuminance values than the other surfaces with maximum monthly mean illuminance values between 45000 – 55000lux (except Dec with max. 10000lux) due to impact of direct solar beam. The exception to this is during the month of June when due to the position of the Helsinki in relation to the Sun at this time of the year the illuminance values on the East and West surfaces are similar to that of the South in the morning and afternoon respectively.

When making a similar comparison on the diffuse vertical illuminance there is less of a discrepancy between the different orientations although the South facing surface still reports the greater illuminance values throughout the year. During March and September, the shoulder months, there is generally a 40-45% reduction in the illuminance values recorded on the other surfaces in comparison to the south facing surface. In June there is generally only a 30% reduction and December a more significant 70% reduction in recorded monthly mean illuminance values. This is with the exception that during the morning hours there appears to be more equal illuminance values in the months of June and September. These variations are shown in Figure 5.20.

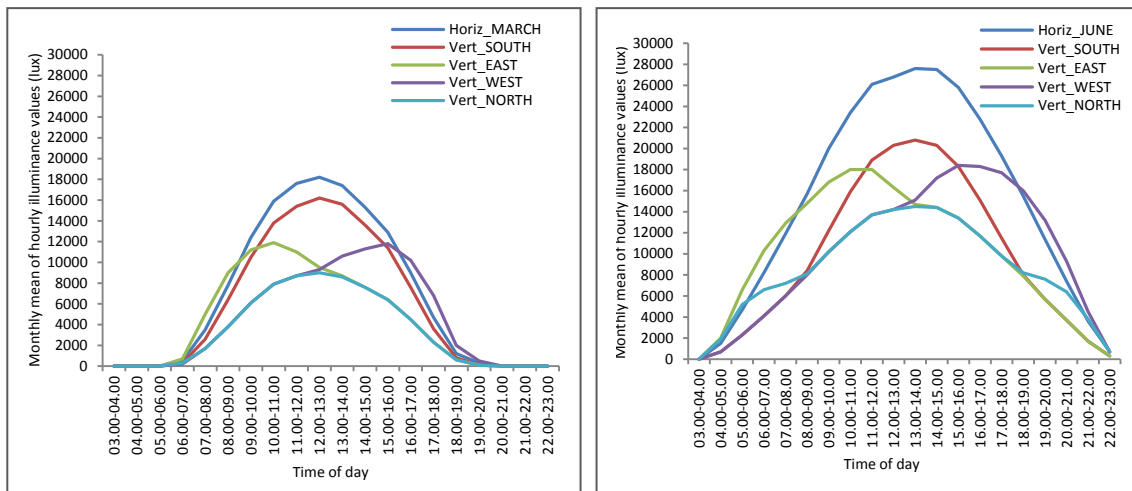


Figure 5.20: Graphs showing monthly mean of hourly diffuse illuminance for vertical surface facing North, South, East and West in Helsinki, Finland extrapolated from climate data from *SATELLIGHT*

This comparison identifies the importance of understanding the difference between the horizontal illuminance at a given locations and the amount that might reach the vertical surface of building facade or more importantly a glazing system. On the surface this may seem like an obvious observation but the difference between two values could be quite considerable if external obstructions were also taken into consideration.

5.4.5 Summary

In order to assess the impact of the specification of glazing within building facades it is necessary to understand the parameters that affect the availability of daylight that reaches the external surface of the window.

Greater detail and increased accuracy of evaluation can be achieved by utilising real datasets. Climate data is available from ground based weather stations but this is limited by the number of locations and a limited surface area that they can cover. Daylight and Solar radiation data is also available from satellites which can provide information for a much wider area of the Earth's surface. This thesis will use data from *SATELLIGHT*, the European database of Daylight and Solar Radiation which provides hourly illuminance values for any location in western and central Europe averaged over a 5 year period. This illuminance data can be extrapolated for both horizontal and vertical surfaces at a given location which provides a clear picture of the amount of light that would be expected to reach the facade of a building.

Using diffuse vertical illuminance data will provide a worst case scenario in terms of the available external illuminance but potentially more realistic for scenarios where issues of glare

and excess solar gain mean that the direct solar component is removed by shading devices or other means.

This section has also shown that it is important to understand the difference in vertical illuminance for the four cardinal points as the orientation of a particular facade or glazing system is a key design decision which may have an impact on the ability of the interior of the building to provide the necessary lighting environment. The data discussed earlier showed that there were differences between the diffuse illuminance values for the different orientations relating to both time of year as well as time of day. This may seem like an obvious assessment but when this is taken into consideration with the effect of the choice of glazing there may be a more significant impact on the internal lighting environment.

Although the traditional methods and metrics for evaluating daylighting design such as the Average Daylight Factor are good rule of thumb calculations they do not include information about the geographical location or the orientation of a particular facade. This in turn might affect the suitability of specific design decisions such as the appropriate specification of glazing. These choices may become more prevalent if current biomedical research into the human non-visual system proves a definitive connection to light received at the eye and well-being.

5.5 Summary and conclusions to Chapter 5

Humans evolved under light from the Sun therefore it is reasonable to assume that inherent biological systems are attuned to respond to the quantity and spectral quality of daylight. This system of photometry is driven by the sensitivities of the visual system in order to maximise visual performance alongside efficiency. As more is discovered about the human non-visual system the current system of photometry may need to be adapted. To support the well being of the building occupant as well as their visual performance, understanding in more detail the quality as well as the quantity of light sources will be important.

Although most architects acknowledge the value of natural light, most building lighting strategies rely heavily on artificial light sources. The spectral power distribution graphs of artificial light sources show that some of these sources produce little light at the shorter wavelengths which have been suggested as important for the non-visual system. If the spectral quality of light is proven to be important to stimulate the non-visual system then a better understanding of how to maximise daylight within buildings will be important.

This chapter emphasised that daylight has an enormous variability, constantly changing in connection to the time of day, the time of year and the location from which it is perceived. This makes it difficult to provide a precise assessment of its ability to deliver the required lighting environment in an internal space. Understanding how this availability changes depending on the chosen location of a building will have an impact on the choice of building components, in particular the glazing materials. An ability to define more specific performance characteristics of building components enables buildings to be more responsive to their individual context.

The external illuminance data for Helsinki highlighted that for some locations, across a year, there are significant periods when the quantity of daylight available is very low. As well as the intensity of available daylight this will have the most significant impact in connection to the timing of light stimulus, the potential importance of which was outlined in Chapter 4. Providing light to stimulate the non-visual system and in turn the well-being of the building occupant has been shown to be about providing the necessary amount of light at the right time of day. This thesis uses Illuminance data from *SATELLIGHT* for the three locations assessed in the Northern hemisphere, each with different latitude. This data provides a basis to the evaluation of the impact that the choice of glazing system has on the light that will reach the building interior.

Chapter 6

Glass and glazing systems

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6 Glass and Glazing Systems

The main aim of this thesis is to investigate whether the specification of glazing has a significant effect on the quantity and quality of light that reaches the internal environments of buildings and therefore the potential of that environment to maintain occupant well-being. The conclusions of Chapter 2 suggest that although there are very few regulations around the provision of daylight within buildings it is regarded as important for the perception as well as the psychological well-being of the people that inhabit the space.

The glazing system used within the envelope of a building is the threshold between outside and inside, the point at which the available daylight enters the building. Chapter 4 of this thesis has shown that quality as well as quantity of light is important to the physiological well being of the building occupants. This chapter now focuses on the effect the glazing has on both the quantity and quality of light within an internal space served and the impact this may have on the light that reaches the occupant's eye.

As outlined in Chapter 1 the development of glass as a building component and the technology both to manufacture but also to construct with it led to the transformation of the internal spaces people inhabit. The ability to design buildings in which greater amounts of daylight could be brought inside whilst protecting against the other climatic elements meant that quality of life was improved. As the development of glass products and glazing continues to progress it has an increasing effect on the quality as well as the quantity of light that penetrates the internal environment of buildings. Understanding to what extent this has a positive or negative effect on occupant well-being will support the specification of appropriate glazing systems to support visual and non-visual systems.

As discussed in Chapter 2 there have been many studies undertaken to evaluate the impact of the lighting environment on the occupants' perception and satisfaction of a given space. It also outlined a more recent study that addressed the impact of different glazing types on the perception of daylight quality, arousal and the switch-on of artificial lighting. This chapter will assess the effect of the specification of glazing systems on the quantity and quality of light that they transmit with a specific focus on the requirements of light as stimulus for non-visual processes.

6.1 The interaction of light and materials

In order to understand how glass as a material reacts to light it is important to take into consideration the physical behaviour of light energy particularly in the visible spectrum as well as the methods for describing the process. The material qualities of a piece of glass or an entire glazing system will affect how it reacts to light.

A *wavelength* describes the distance between peaks or troughs of a wave and *frequency* denotes the number of waves passing a point in space measured per second. Ultra Violet and Visible light are absorbed by different materials to varying degrees, in other words light travels through the material, absorption takes place and a reduced amount of that light emerges from the material. When white light is directed at a coloured solution some wavelengths of that light are absorbed. The transmitted light that the viewer receives is now coloured because it is missing some wavelengths of the original white light, for example a substance which absorbs blue and green light appears yellow-red. The shorter the wavelength of light the more likely there is to be interaction with material compounds; this is why blue light is often the first absorbed or diffracted colour when white light is shone through a cloudy substance. This is also the reason why the sky appears blue as the shorter wavelengths of blue light from the Sun are scattered by the Earth's atmosphere. All materials affect the intensity and spectral distribution of daylight, this property is therefore important to the choice of glazing systems within a building envelope.

To understand the amount of daylight that reaches a space through the glazed opening of a facade it is important to understand the relationship between transmittance of radiant energy through a compound and the absorbance of energy by that compound. Most experimental measurements as well as technical data from manufacturers relating to glazing performance are given in terms of transmittance (T) of light energy. Transmittance can be defined by the intensity of light after it passes through a given material divided by the initial intensity of light, defined by Equation 6.1,

Equation 6.1

$$T = I/I_0$$

where:

I is intensity of light that passes through a material

I_0 is initial intensity of light

As a beam of light passes through a material or compound the amount of light energy in any unit volume is proportional to the intensity of incident energy multiplied by the absorption

coefficient. The intensity of the incident beam drops exponentially as it passes through the material. The relationship between absorbance and transmittance can be described in a number of ways denoted by Equation 6.2 or Equation 6.3 below

Equation 6.2

$$A = -\log T = -\log (I/I_0)$$

Equation 6.3

$$T = 10^{-A}$$

where:

T is transmittance of light radiation

A is absorbance of light radiation

This is a direct relationship where if transmittance is 100% and all light passes through a material absorbance is zero and if all light is absorbed then transmittance is zero but absorption is infinite. Unlike with the equation for transmittance a connection can be made between absorbance and other factors relating to the material properties of the sample being tested. The Beer-Lambert Law describes the linear relationship between absorbance and concentration of the absorbing material. The transmittance of light through a compound has an exponential relationship with the concentration of the compound it is travelling through. As the thickness of the compound increases the amount of light that is transmitted decreases. In comparison the relationship between absorption and the concentration of the compound is linear; the amount of radiant energy absorbed is directionally proportional to the concentration of the compound material. The concentration of the compound can be described as the amount of absorbing material in its path length. The amount of light emerging from a given sample is affected by the concentration of this material as well as the distance the light has to travel through the sample and the probability that the photon of that particular wavelength will be absorbed by the material. This is described as absorbtivity or the extinction coefficient.

The Beer-Lambert law describes the absorbance of light by molecules in a solution and is described in Equation 6.4 below

Equation 6.4

$$A = \epsilon bc$$

where:

ϵ = molar absorbtivity ($L \text{ mol}^{-1} \text{ cm}^{-1}$);

b = path length of the sample (cm);

c = concentration of compound in material (mol L^{-1}).

Using this mathematical tool it is possible to express how light is absorbed by a material, the molar absorptivity and how this reacts to different wavelengths of light. Absorbance is directly proportional to the other parameters involved such as concentration or density of that material compound as well as sample length, or the distance the light has to travel. It is therefore often more straightforward to describe the interaction of light with a material using absorbance rather than percentage transmittance. This equation can be linked to the transmittance value as it will still be necessary to calculate the absorbance value therefore the equation can be modified as shown below.

Equation 6.5
$$A = -\log(I/I_0) = \epsilon bc$$

As the percentage transmittance is often given as information about the performance of glazing systems it would therefore be possible to work out the absorbance of that material, and therefore the affect the compound was having on the available energy denoted in Equation 6.6.

Equation 6.6
$$A = 2 - \log_{10}\%T$$

This thesis is looking to understand the quality and quantity of light that a variety of glazing systems allow to penetrate the internal environment of buildings. This therefore concerns itself with transmission of light and the amount of light energy that is transmitted through an individual glazing system across the electromagnetic spectrum. Being able to measure the intensity of light transmitted and absorbed at different wavelengths will give a better understanding of the quality of light within a space. This is of particular importance when you consider the different photoreceptors within the retina have different spectral sensitivity therefore the spectral distribution of light that is received at the eye is as important as the quantity. These factors are central to the circadian, endocrine and neurobehavioural processes connected to these photoreceptors and in turn have potential health implications as discussed in Chapter 4.

It is important to understand the performance of modern glazing systems and the impact improving technology is having on the quality of light transmitted to internal environments. It is necessary not only to know the basic optical properties of the glass but the spectral distribution of the light transmitted. This thesis hypothesises that the choice and specification of glazing system may affect both the quantity and quality of light available to the building occupant. This in turn could have an impact on the light information that is received at the eye and sent to the brain and in the long run affect their health and well being. In order to test this theory it is important to establish the actual reductions occurring at the parts of the spectrum

shown to be important for human physiological well being. The tools available to do this are physical testing using a spectrophotometer as well as the use of existing glazing databases that provide spectral information. This thesis uses both approaches to establish confidence in the larger testing datasets available.

6.1.1 Comparison of data sets

The International Glazing Database (IGDB) provides optical data of a wide range of glass and glazing samples provided by manufacturers and is used as source information for the analysis of the performance of glazing systems within software such as *Optics6*¹. It should be noted here that guidance for manufacturers providing optical information to the International Glazing Database states that the physical measurements of glass and glazing samples should be undertaken using a spectrophotometer with an integrating sphere (National Fenestration Rating Council , 2013). This is particularly in reference to multi-layered samples in order to ensure that all light transmitted by the sample is captured by the detector.

In order to establish confidence in the larger dataset a series of physical tests were undertaken using a laboratory based spectrophotometer as described in Chapter 3. Although the glazing sample tests for this thesis were not able to be undertaken using an integrating sphere, access to a laboratory grade FT-IR spectrophotometer provided the opportunity to run an analysis of a small range of glass samples. It was considered that if these physical measurements did not show greater transmittance values than those provided by the International Glazing Database there could be confidence in the accuracy.

The Fourier Transform Infrared (FT-IR) spectrophotometer takes readings of transmittance as well as absorbance and can provide data in micro nanometre bands providing the opportunity for detailed analysis of the interaction of light with a particular material or substance. Spectral information provided within the International Glazing Database ranges from 5nm to 10nm bands providing a more simplified description of the characteristics of each glazing sample. The comparison of the two sets of data is shown in Figure 6.1 to Figure 6.4.

These figures show that the data from physical testing has a close correlation to the data from the International Glazing Database extracted through *Optics6*. As noted earlier the *Optics6* data presents a slightly greater transmittance across the visible spectrum as would be expected based on the methods used to measure the samples.

¹ *Optics6* has been developed by Lawrence Berkeley National Laboratory and can be downloaded from the website <http://windows.lbl.gov/software/window/window.html>.

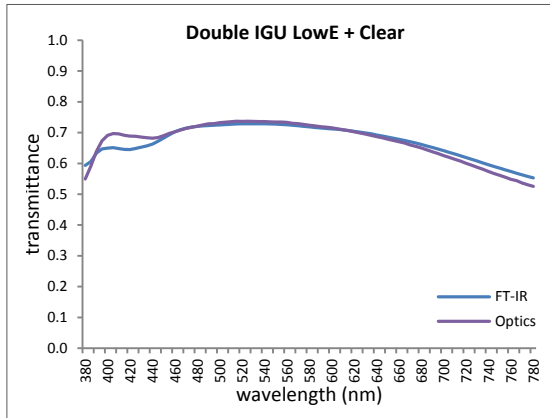


Figure 6.1: Comparison of SPD data for a Double IGU with LowE +clear glass from *Optics6* and physical testing using an FTIR spectrophotometer

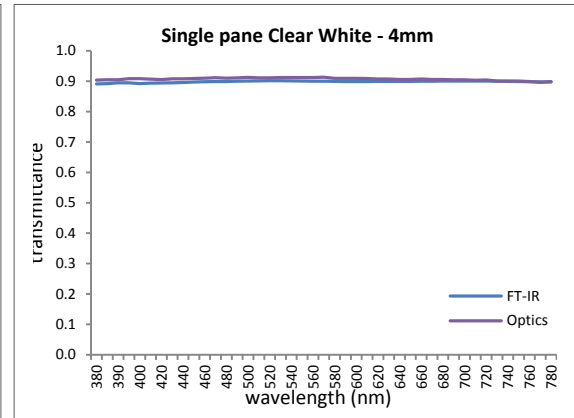


Figure 6.2: Comparison of SPD data for Single Clear White glass sample from *Optics6* and physical testing using an FTIR spectrophotometer

The Single Clear White glass sample, in Figure 6.2, and the Double LowE with clear outer pane, in Figure 6.1, both show a $\leq 2\%$ difference between the two sets of data within the wavelength range 435 - 760nm. This consistency between the two datasets was also shown with the bronze and grey body-tinted glass samples shown in Figure 6.3 and Figure 6.4, although the *Optics6* data presents a slightly greater transmittance across the visible spectrum for these two samples. There is also a small but measurable difference between the two sets of data at the longer wavelength end of the spectrum.

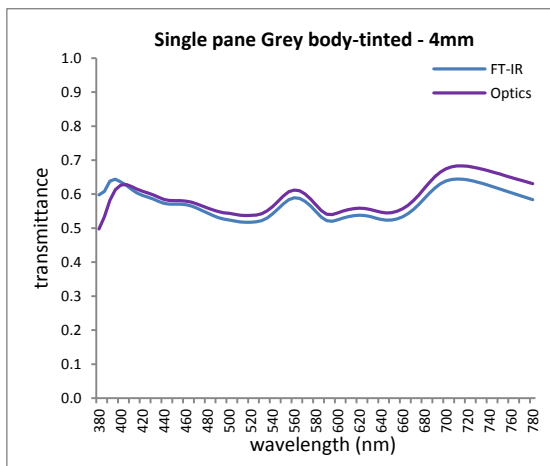


Figure 6.3: Comparison of SPD data for a Single pane grey tinted glass sample from *Optics6* and physical testing using an FTIR spectrophotometer

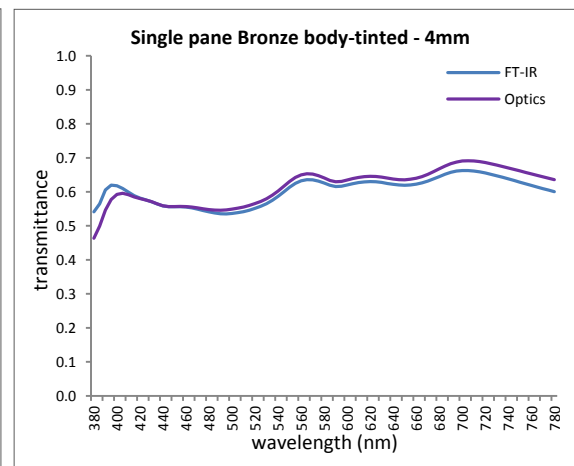


Figure 6.4: Comparison of SPD data for a Single pane bronze tinted glass sample from *Optics6* and physical testing using an FTIR spectrophotometer

This short study provides confidence in the optical information provided by the International Glazing Database and used with glazing analysis software such as *Optics6* and *WINDOW*. Information for a range of glazing samples from this database and analysed within both *Optics6* and *WINDOW* software will be used in the rest of the thesis.

6.2 Transmission properties of glass

As identified in previous chapters initial research findings suggest that certain wavelengths are important to physical processes in the human body such as the circadian system, the resultant effect of glass on the spectral distribution of light that reaches the internal space could therefore be significant key factor in maintaining these processes. To understand the spectral distribution of light received by a space it is necessary to identify the effect of the material composition of the glass as discussed above, as well as the build up of the glazing system which could include films or coatings to different layers of the glass or gases used to fill internal cavities. The maintenance of the windows can also have an impact on the amount of light that is transmitted; it may also have an effect on the spectral distribution either by reflecting or absorbing certain wavelengths of light.

As was indicated above there are three processes involved when light radiation falls on any transparent material; reflection, absorption and transmission and they can be expressed simply as a fraction of the total light falling on that surface as defined in Equation 6.7 below.

$$\text{Light} = R + A + T$$

Equation 6.7: Definition of processes involved when light falls on a transparent surface

where:

- R is reflectance of light radiation from a material
- A is absorptance of light radiation by a material
- T is transmittance of light radiation by a material

Most of the glass used for architectural purposes is predominantly transparent with a small amount of reflectance and absorption but to identify the effect of these processes the solar spectrum and the optical properties of the material have to be considered.

The percentage transmittance of any piece of glass relies on a number of different factors; the type of glass, how it was made and the specific breakdown of material components as well as to a certain degree the thickness, the angle of incidence and the specific wavelength of the light falling on the glass. Window or plate glass can typically transmit up to 90% of UV-A and visible radiation as long as the iron oxide ($\text{Fe}^{2+}\text{O}^{3-}$) content is lower than 0.035%. If the iron oxide content is higher transmittance will be decreased. The atomic nature of this material cannot absorb light energy in this range but the energy in the shorter wavelengths of UV-B and UV-C are such that it vibrates the electrons and the light is absorbed therefore stopping these harmful wavelengths pass through the glass (Harth, Tasche, Unnewehr, & Weller, 2009).

6.3 Development of glazing systems

Since the revolutionary use of glass in the construction of Crystal Palace by Joseph Paxton in 1854 developing existing techniques in order to manufacture enormous quantities of flat panes of glass, the process for mass production of glass has been driven to produce larger and purer sheets of glass. Although there are still a significant percentage of windows with single glazing as part of buildings constructed before the tightening of energy performance within building regulations, the majority of new buildings include double or triple glazed window systems. The addition of multiple layers of glass provides an opportunity to improve the performance of the window system as well as influence the aesthetics of the building facade. This section will give a brief overview of the development of glazing systems, the range of components and the process with which they are manufactured.

6.3.1 Manufacturing process and different glass types

Glass can be manufactured in different ways which can have an impact on its performance characteristics. Most large sheets of glass used in buildings today are float glass, made by floating molten glass over molten tin and annealing slowly to produce flat smooth sheets of transparent glass. As the surface is heat polished there is no need for the glass to be grinded and polished again resulting in a very smooth surface. Before the invention of float glass in the 1950s by Alastair Pilkington the only way to produce large sheets of transparent glass was a process in which molten glass was drawn onto a flat surface and smoothed out with a roller. It often produced distortions in the glass made worse as the sheet size got bigger; this traditional method is now only used for small window lights or in historic refurbishment work.

The modern method for rolled glass now involves passing a continuous ribbon of glass through two water-cooled rollers; the gap between the rollers defines the thickness of the glass which can be anything from 3 to 15mm. Rolled glass is used for various glass products such as patterned and wired glass. Profiled glass is also produced using this method where the U-shape is created by turning up the edges of narrow ribbons of glass through 90 degrees using vertical rollers. Light transmittance properties of rolled glass are generally poorer than those of float glass as it can be affected by the thickness and surface texture of the glass product.

There are a number of different types of glass, their characteristics defined by the manufacturing process used and the exact compounds from which they are made. Most architectural glass is soda-lime glass and it is one of the least expensive to make. Made from 60-75% silica, 12-18% soda and 5-12% lime it is the most common type of glass and is also

used for bottles as well as many other consumer items. Lead glass is made using a high percentage of Lead Oxide which creates a fairly soft glass that is generally used for glass art as well as electrical appliances. Borosilicate and Aluminosilicate glass are both silicate glasses containing different oxide compounds, Boric and Aluminium oxide respectively. Both these glasses have an increased resistance to high temperature and chemical corrosion and are used for things such as headlight bulbs and cooking equipment. A version of borosilicate glass is 96% silica glass which has been melted to remove almost all non-silicate elements making it heat resistant up to temperatures around 1,652°F and is therefore often used for fire protection glass within buildings.

Due to its inherent value as a building component, a number of processes have been devised to improve some of the poorer performance characteristics of glass, making it possible to use in an even wider variety of circumstances. For example float glass can be reheated and rapidly cooled which can make it up to four times stronger, often called tempered or toughened glass and used as safety glass. Laminated glass involves a process of sandwiching a sheet of polymer between two layers of float glass and is often used to diffract light but can also be used for increased sound proofing or for other specialist glasses such as bulletproof glass. The optical properties of these glasses can vary and a range of these glass types have been given diffuse transmission factors by the Building Research Establishment (BRE) ranging from 0.20 for laminated insulating glass to 0.85 for 6mm clear float glass with 1.0 being effectively full transmission.

6.3.2 Body-tinted glass

The colour of glass can be changed by the addition of metal oxides such as selenium oxide or cobalt oxide to the composition during the manufacturing process. Standard float glass with a typical composition has a green tint due the presence of iron oxide this is particularly apparent at the edge of each pane. Ultra clear or colourless glass which is often termed 'Clear White' glass is possible to achieve by reducing the iron oxide content, the greater the amount of iron oxide within the glass the more green the appearance. This process of modification is possible with other metal oxides for example if cobalt oxide is added it gives the glass a grey appearance and selenium oxide gives a bronze appearance. Opal glass which is light permeable but not transparent can be produced by adding fluorine compounds, phosphates or tin oxide. By adding other materials to the base glass is it possible to alter the ratio of absorbance to transmittance of solar radiation. This in turn reduces the potential for overheating to occur due to excess solar gain within the building interior as well as increases

the temperature of the surface of the glass. These body-tinted panes can often be used in double glazed units with a clear inner pane for improved solar performance.

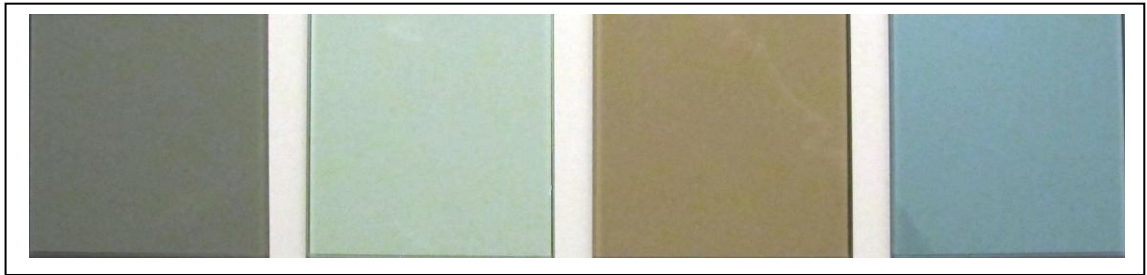


Figure 6.5: Four different single pane body tinted glass samples

Tinted glasses absorb a large amount of the radiation and release it at a later stage as heat energy; the amount is dependent on the thickness of the glass as well as the degree of tinting. This can reduce the g-value to around 30% but a consequence of this is that this type of glass experience high surface temperatures. The colour tint of these glasses is not necessarily as apparent externally as some coated glasses as they do not have such high reflectance values. The reduced light transmittance of tinted glass is usually the most apparent visual characteristic. The impact on the light transmittance of tinted float glass is dependent on the metal oxide that has been added to the composition. For example with a 6mm green body-tinted glass pane with an increased amount of iron oxide has a light transmittance of 0.75 whereas with the same thickness bronze tinted glass which contains additional selenium oxide has a light transmittance of only 0.50. The light reflectance values of these products on the other hand are virtually the same with 0.07 and 0.06. This suggests that selenium oxide has a different reaction to light than iron oxide absorbing more energy than iron oxide. The light transmittance values are reduced even further when you look at a 6mm pane of grey tinted glass that includes cobalt oxide in the composition of the glass where the light transmittance reduces to 0.44.



Figure 6.6: Photograph of the external facade of a building with a large percentage of body-tinted glazing (authors own)

6.3.2.1 'Clear-white' glass

The development of glass with a high percentage solar transmittance to satisfy the requirements of maximising solar radiation collection for solar water heating or photovoltaic panels has resulted in the production of an ultra clear glass. Unlike with body tinted glass to produce 'clear-white' glass the iron oxide in the base glass material, the compound which gives glass its green hue is reduced so that the glass appears to be completely clear or clear-white as it is described by some manufacturers. The transmittance of this type of glass can be anything up to 92-93% for a 6mm single pane of glass with a SHGC of approximately 0.9 and a U-value of approximately $5.7 \text{ W/m}^2\text{K}$. This type of glass can be used within some multi-layered glazing systems to increase the visible light transmittance to meet specific requirements such as locations where there was a low level of external illuminance.

6.3.3 Coating and glass films

Another way to improve the performance of glass and glazing systems is to apply a coating or film to one of the surfaces of the glass generally to one of the internal layers or surfaces. Most coatings used on the surface of glass, absorb some of the solar radiation; this will reduce the U-value of the glass as well as the visible light transmitted. Tin oxides are often used to improve thermal resistance of the glass by reducing the emissivity. If this kind of coating is applied it can reduce the emittance to approximately 13% whereas the emittance of a normal glass surface is over 90%. There are two ways of coating the surface of glass, described as *online* and *offline*.

6.3.3.1 Online coating

The surface of sheet glass can be treated with a variety of coatings during the manufacturing process which is described as online coating. This takes place during the solidification process while the glass is hot and produces a strong bond between the materials. This is the most likely process used for coatings that are going to be on the external face of the glass or glazing exposed to the elements as it provides a more durable finish. This is more typical for some types of solar control coating or reflective coating as they tend to be more effective when positioned on the outer pane or face of a glazing system. These types of coatings are generally not as effective as off-line coating but because they are applied during the float process when the glass is still hot their durability means that they are easier to handle and process. This means that it is possible to toughen or laminate them with other glass products and in some instances they are suitable as single glazed units.

6.3.3.2 Offline coating

The process of coating can also take place once the glass has cooled, solidified and been cut which is described as offline coating. Panes of glass are dipped into chemical solutions then dried and fired or through a process where different metals are evaporated onto the glass surface whilst in a vacuum. This method of coating can leave the surface and coating more vulnerable to environmental influences therefore surfaces coated offline are normally located on the inside of a multi-pane window system for protection.

Although these processes have been applied for a long time, in the last decade the most common process has been to use magnetron sputtering of materials. This process can give a wide range of coatings with a variety of compositional properties affecting colour, reflectivity and thermal performance. The process involves introducing argon gas into a vacuum chamber at which point glow discharge plasma occurs. Electrons are removed from the argon leaving positively charged ions. These ions have a very high momentum and when they make contact with the target cathode they eject atoms of the cathodic material which re-condense on the pane of glass below. Most non-metallic or alloy material can be sputtered. Using argon in the vacuum chamber will provide a metallic coating but if oxygen or nitrogen is used the resultant coating will be an oxide or nitride (Pilkington).

The light transmittance of the glass will depend on the material property of the coating as well as the thickness. Higher levels of thermal insulation as well as light transmission can be achieved by using off-line coatings rather than online coatings. Solar control and low-E glasses are typically coated; solar control glass is normally coated with a metallic material which allows

a high percentage of light reflection in the infrared range. Although a good level of light transmittance in the visible range is a requirement it is inevitable that there will be a reduction in performance in this area with this type of coating in comparison to other glasses. Coated glass can also be tinted which will have a further impact on the light transmittance. It is also possible to use coatings with anti-reflection properties which allow a greater amount of light transmittance; this coating can reduce the normal reflection value of 8% to 1%.

6.3.3.3 Position of coating

Some glazing units are designed with the intention of improving the thermal performance, to reduce heat loss whilst maintaining solar gains. These glazing units, instead of incorporating a coating on the external surface, will introduce an infrared-reflective coating to the inner pane preventing heat emissions from the inner to the outer pane; the heat is absorbed and re-emitted into the room. It is possible to apply the coating to the inner surface of the outer pane, facing the cavity, but this would be less effective and therefore indicates that the position of the coating is important to the effectiveness of the IGU (Harth, Tasche, Unnewehr, & Weller, 2009).

Each glazing manufacturer tends to favour a particular approach when it comes to the build-up of IGUs and therefore the position of the any coating or film on the glass. This will depend heavily on the choice of material for the coating as well as providing a further opportunity to maximise the performance of the glazing system.

6.4 Performance characteristics of glazing systems

The function and geographical location of a building have a significant bearing on the specific requirements for the performance of a glazing system. There can be a wide variety of parameters influencing the successful performance of a glazing system including sufficient reduction in solar gain to the importance of energy efficiency therefore improved thermal resistance. The success of the external appearance of a building can also be influenced by the suitable aesthetic of the chosen glazing system. It is often the case that there is not just one but multiple requirements placed on the performance of the glazing system but one of these parameters will ultimately drive the specification.

6.4.1 Glazing Units

A single glazed window transmits the majority of the available daylight and it can only rely on the properties of the glass and the frame that houses it to reduce solar gains into the internal space as well as the loss of valued heat energy to the outside. Poor performing single glazed windows are often one of the factors in increased energy consumption in buildings particularly in temperate or cooler climates as more energy is required to cool internal spaces or heat them where excess heat is lost through glazing. It is no longer very common to see single glazed windows in new buildings unless this is a specific planning condition due to its poor thermal performance and the stringency of the building performance regulations discussed in Chapter 2. The thermal resistance of glass can be improved by increasing the number of layers of glass to create a glazing unit separated by a sealed cavity. The build up of the glazing unit has an impact on the reflectance, absorbance and transmittance of solar radiation, for example the Chartered Institute of Building Services Engineers (CIBSE) also notes in its Lighting Guide LG10 (CIBSE, 1999) that the layering of panes of glass improves the thermal efficiency by around 15%.

6.4.2 Thermal performance

The transmittance of light has to be balanced with these other design parameters and one of the most significant is heat loss due to the inherently poor thermal resistance of glass as a material. The U-value describes the thermal resistance of a material, its ability to transmit energy measured in Watts/m²K. A poor conductor of heat is the optimum to reduce heat loss and therefore energy loss through the external fabric of a building. A key parameter for the performance of a glazing system is the ratio of light transmittance to its U-value. The thermal performance of a single pane of glass is very poor with a high U-value which can cause a

number of problems, particularly excessive heat loss in colder climates and particularly during winter months in temperate climates. However the transmittance values for visible light are also high therefore providing large amounts of natural light to internal spaces, therefore those with a high ratio of light transmittance to U-value will give less heat loss for the same daylight penetration. This is a performance characteristic that many designers look for in the specification of glazing systems within buildings.

Due to the inherent poor performance of the material compounds of glass and its absorptivity coefficient increasing the thickness of the pane of glass itself does not have a significant impact on the thermal resistance. A comparison of the U-value of different thicknesses of glass highlights this fact and is shown in Table 6.1. This table and the following two tables have been produced from data derived from glazing simulation software, *Optics6*. To improve the thermal performance of glazing systems in terms of heat loss a number of techniques have been developed by glazing manufacturers. Increasing the number of layers of glass for example in a double glazed or triple glazed unit with a sealed cavity between them reduces the amount of heat energy lost. With the cavity of double and triple glazed unit just filled with air the thermal performance can be doubled in comparison to a single monolithic pane due to the interaction with the air molecules within the cavity. Further improvement is achieved by filling the cavity with a low emissivity gas such as argon or krypton therefore reducing the conducted and radiant heat loss through the glazing unit.

Table 6.1 also shows that an increase in thickness of a glazing unit with double or triple layers of glass also has an effect on the transmittance of visible light but this is not significant when just using multiple layers of clear float glass. It also shows that the introduction of a low emissivity gas such as Argon into the sealed cavity within the glazing unit improves the U-value by approximately 0.2-0.3W/m²K but does not affect the transmittance of visible light.

Table 6.1: Typical U-values and Transmission for Clear Float Glazing Systems extracted from *WINDOW*

ID	Glazing type	T _v	U-value (W/m ² K)
001	Single 3.0mm	0.90	5.83
008	Single 6.0mm	0.88	5.74
087	Double 6mm + 16mm cavity (AIR)	0.79	2.68
091	Triple 6mm + 16mm cavity (AIR)	0.70	1.70
108	Quadruple 6mm + 16mm cavity (AIR)	0.63	1.35

Using clear panes of glass within double or triple glazing units has an impact on the thermal performance as shown above, reducing the U-value by half. However these window systems still perform poorly in comparison to other building components. Glazing manufacturers therefore apply coatings or films to glass to improve its thermal resistance by reducing the emissivity as described above; the development of more effective and efficient coatings is the focus of large investment by glazing manufacturers. By incorporating these coatings into multi-layered glazing units it is possible to combine the advantages of both approaches to improve performance. Low-emissivity (LowE) coatings are generally applied to the inner surfaces of the outer pane of the glazing unit but they can also be applied to the inner surface of the inner pane. The position of the coating is important to maximise the effectiveness of the properties of the coating as well as protect it from external elements. Table 6.2 shows the effects of the low-E coatings when compared to the values shown in Table 6.1 without the coating.

Table 6.2: Typical U-values and Transmittance for Clear Float Glazing Systems with Low-E coatings extracted from *WINDOW*

ID	Glazing type 6mm glass, 16mm cavity (AIR)	T _v	U-value (W/m ² K)
087	Double Inner clear, Outer clear	0.79	2.68
028	Double Inner Low E, Outer clear	0.69	1.29
096	Triple Inner LowE, Outer clear (x2)	0.62	1.01
112	Quadruple Inner LowE, Outer clear (x3)	0.56	0.85

The material components of the coatings as well as the combination and build up of the glazing units vary between manufacturers, the specific nature of the material components often protected intellectual property of the manufacturer. Although the aim of low emissivity coatings is to reduce the heat loss through the glass they can also have an impact on the transmittance of light as shown below in Table 6.3. In this table the U-values are not shown as it would not be relevant as these products would not be used on their own as a building component. This table shows the difference between low emissivity coatings produced by four different manufacturers as well as the position within the glazing unit and the effect on the visible transmittance. It also identifies the impact on the appearance of the glass which gives an indication of the difference between material components within the coatings.

Table 6.3: Comparison of specification and transmittance of four low emissivity coatings extracted from *WINDOW*

ID	Glazing type	Appearance	Coating side	T _v
021	LowE_A	Clear	Back	0.69
022	LowE_B	Neutral	Back	0.70
023	LowE_C	Light Gold	Back	0.48
024	LowE_D	Clear	Front	0.77

Table 6.4 shows these same products within a more typical double glazed unit and the impact on the visible transmittance values as well as the U-values of these glazing units. Due to the position of the coating on the various products the glazing units are set up differently with the LowE coated glass typically as the outer pane but also positioned as the inner pane.

Table 6.4: Comparison of transmittance and U-value of four LowE glazing units extracted from *WINDOW*

ID	Glazing type 6mm glass, 16mm cavity (AIR)	T _v	U-value (W/m ² K)
025	LowE_A + clear	0.61	1.31
026	LowE_B + clear	0.62	1.32
027	LowE_C + clear	0.43	1.34
028	Clear + LowE_D	0.69	1.29

Some manufacturers also use low emissivity coatings on both internal and external panes of glass within a glazing unit to further improve the thermal performance of the glazing system. The effect of this can be seen in the comparison in Table 6.5. This tends to be more effective when it forms part of a triple glazed unit as is evident by the values in the table below. The ultimate aim of this type of glazing system is to improve the U-value therefore reducing the figure as far as possible whilst maintaining as high a value for visible transmittance as possible. For example, sample #99 shown in Table 6.5 provides slightly better performance characteristics in terms of visible transmittance than sample #98 but not with respect to the U-value, both Triple Glazed units with LowE coatings.

Table 6.5: Comparison of high performance Low E glazing systems with one or two layers of coated glass extracted from *WINDOW*

ID	Glazing type IGU: 6mm glass, 16mm cavity (AIR)	T _v	U-value (W/m ² K)
123	Double (LowE_B) Inner Clear, Outer LowE	0.62	1.3
123	Double (LowE_B) Inner LowE, Outer LowE	0.61	1.3
099	Triple (LowE_B) Inner Clear, Middle clear, Outer LowE	0.56	1.0
100	Triple (LowE_B) Inner Low E, Middle clear, Outer LowE	0.55	0.8
096	Triple (LowE_D) Inner LowE, Middle clear, Outer Clear	0.62	1.0
098	Triple (LowE_D) Inner Low E, Middle clear, Outer LowE	0.48	0.8

To further increase the thermal performance of the glazing unit it is possible to reduce the transmittance of solar radiation by incorporating a body-tinted glass or a coated glass as the outer pane to either increase the absorptance of solar radiation or to increase the amount that is reflected away from the surface externally. This type of glazing unit can also have a significant impact on the transmittance of visible light with values being reduced to 45% for double glazed units and 40% for triple glazed units. Comparing Table 6.6 with Table 6.1 and Table 6.2 shows how tinting the outer pane of glass can further affect the properties of the glazing systems.

Table 6.6: Typical U-values and Transmittance for Tinted Float Glazing Systems with Low-E coatings extracted from *WINDOW*

ID	Glazing type 6mm glass, 16mm cavity (AIR)	T_v	U-value (W/m ² K)
076	Double (blue tinted) Inner Low E, Outer blue tinted	0.44	1.7
103	Triple (blue tinted) Inner Low E, Middle clear, Outer blue tinted	0.40	1.3
113	Quadruple (blue tinted) Inner Low E, Middle clear x2, Outer blue tinted	0.36	1.0
080	Double (bronze tinted) Inner Low E, Outer bronze tinted	0.4	1.7
105	Triple (bronze tinted) Inner Low E, Middle clear, Outer bronze tinted	0.36	1.3
115	Quadruple (bronze tinted) Inner Low E, Middle clear x2, Outer bronze tinted	0.32	1.0

The visible transmittance values for glazing units within Table 6.6 are significantly reduced, in particular the triple glazing unit with bronze tinted outer pane and both quadruple glazing units. These glazing systems would substantially reduce the daylight which penetrated the internal spaces within the building. Depending on the external illuminance available this could affect both visual performance as well as non-visual photoreception, not providing enough light to stimulate the physiological processes defined in Chapter 4. Research by Boyce et al (1995) which looked to define the minimum acceptable transmittance of glazing for user satisfaction suggested that it should be in a range 25% to 38%.

6.4.3 Solar Control

As well as transmitting visible light, glass also transmits and absorbs other parts of the electromagnetic spectrum. For example glass may reflect the majority of long wave solar radiation but it is also capable of re-emitting the energy that it absorbs as heat. This can cause problems of overheating when the sky is clear of clouds and there is a large amount of solar

radiation. In particular this occurs in places where solar altitude is highest near the equator or during the summer months at locations in the northern hemisphere due to their increased proximity to the sun. Although it reflects most Infra-red (IR) wavelengths from solar radiation clear float glass can transmit some near-IR wavelengths. These wavelengths are then absorbed by the surfaces within a given room and re-radiated at longer wavelengths which cannot be transmitted or expelled by the glazing unit and are therefore reflected back into the room. This can be described as the Greenhouse effect.

Solar Heat Gain Coefficient describes the ability of a given glazing system to block heat from the Sun and is often used as a replacement for the shading coefficient providing a suggestion of a window's shading ability. It is a function of the solar transmittance and solar absorptance of each layer of the glazing system and the inward flowing fraction of thermal energy. It is given as a number between 0 and 1, the lower the number the more effective the glazing system is at reducing solar heat gain. It is similar to g-value in that it describes the total amount of solar energy that reaches the room interior from direct transmittance as well as heat energy emitted into the room that was initially absorbed by the glazing system. Beyond its ability to reduce solar gain another key parameter for solar control glass or glazing is the ratio of light transmittance to total solar transmittance. For example for some tinted glazing this can be near 1 as a reduction in total solar transmittance means a similar reduction of visible transmittance. Excessive absorptance of heat energy can also be a problem when using body-tinted or monolithic panes of glass as they can often become quite warm emitting heat energy back into the room interior.

Table 6.7 provides performance information for a few simple double glazed systems with body-tinted glass as the outer layer. It includes the total solar transmittance as well as the reflectance and absorptance from the outer layer of the double glazed unit. It also includes the SHGC and visible light transmittance values. In terms of providing a successful internal lighting environment a glazing system ideally needs to have a low SHGC value with a high visible transmittance value. For example sample #77 provides the best compromise with a low SHGC whilst maintaining the highest visible transmittance value apart from the clear glazing. It is quite common to see blue-tinted glazing used in locations where large amounts of glass are preferable to maximise a particular view, but the potential for solar gain can be high. Keeping the visible transmittance value as high as possible at the same time gives the building occupant the perception that the space has large amounts of natural light.

Table 6.7: Solar and optical properties of a range of double glazed units with body tinted glass extracted from *WINDOW*

			Solar				Light	
ID	Glazing type IGU: 6mm glass, 16mm cavity (AIR)		<i>T</i>	<i>R</i>	<i>A</i>	SHGC	<i>T_v</i>	<i>R_v</i>
	Double							
	Outer	Inner						
087	Clear	Clear	0.61	0.11	0.17	0.66	0.79	0.14
081	Green	Clear	0.22	0.06	0.71	0.23	0.46	0.08
077	Blue	Clear	0.28	0.06	0.62	0.3	0.48	0.08
079	Bronze	Clear	0.37	0.07	0.48	0.41	0.43	0.08
078	Grey	Clear	0.32	0.06	0.06	0.35	0.39	0.07

In a similar way to low emissivity or LowE glass coatings described above which improve the thermal performance of glass, manufacturers have developed coatings and films to improve the solar control of glazing products. Although designed to alter the interaction of the glass with solar radiation these coatings also have an inherent affect on the visible transmittance to varying degrees as shown in Table 6.8. This affect is dependent on the material compounds within the coating and to a certain degree on the position of the coating within the glazing unit. All the glass products in the table below provide a coating on a clear glass substrate so the performance characteristics should not be affected by the base product. Depending on the material properties of the coating they also provide a specific colour appearance when applied to the glass substrate, this may also form part of the aesthetic design of the building envelope.

Table 6.8: Description and visible transmittance values for a range of solar control glass products extracted from *WINDOW*

Glazing type	Appearance	Coating side	<i>T_v</i>
SolarControl_A	Grey	Back	0.42
SolarControl_B	Grey Blue	Back	0.65
SolarControl_C	Clear	Back	0.67
SolarControl_D	Reflective Clear	Front	0.67
SolarControl_E	Clear	Back	0.60

Incorporating these glass products into a double glazed unit shows the impact that the different coatings have on the performance characteristics in a more realistic scenario as it is very rare that any of them would be used on a single glass pane. Most solar control coatings

are positioned on the internal face of the exterior pane as they typically work by reflecting or absorbing certain parts of the electromagnetic spectrum. The performance characteristics of these coatings within a standard double glazing unit are shown in Table 6.9 including the total solar transmittance and total visible transmittance as well as the solar heat gain coefficient (SHGC). The visible transmittance remains high for two of the glazing units but they also have quite high SHGC which means that they do not perform as well as the other systems in terms of solar shading. Both coatings provide a clear appearance whereas the coating that is most effective presents a grey appearance. This might mean the presence of cobalt oxide which can also be added to glass substrate to give a grey tint.

Table 6.9: Performance characteristics of a range of solar control coatings within double glazed units extracted from *WINDOW*

		Solar				Light
ID	Glazing type IGU: 6mm glass, 16mm cavity (AIR)	<i>T</i>	<i>R</i>	<i>A</i>	SHGC	<i>T_v</i>
039	SolarControl_A + clear	0.2	0.3	0.5	0.2	0.37
040	SolarControl_B + clear	0.4	0.2	0.4	0.4	0.57
041	SolarControl_C + clear	0.3	0.3	0.3	0.4	0.6
042	SolarControl_D + clear	0.5	0.2	0.2	0.5	0.6
043	SolarControl_E + clear	0.4	0.1	0.5	0.4	0.53

These two approaches to changing the inherent characteristics of glass, either by adding other compounds to the base substrate such as with body tinted glass or adding a layer of different materials through coating the surface of the glass, can also be combined. This has a more significant impact on the solar performance of the glass as well as the visible transmittance as shown in Table 6.10. It can also have a significant impact on the aesthetics of the exterior of a building as the appearance of the glass can be substantially altered.

The table below shows some of the same solar control coatings from Table 6.9 applied to a green body-tinted substrate which was shown in Table 6.7 to have the lowest SHGC. Even just within a double glazed unit the SHGC for these three coatings is improved to the same value of 0.2. The visible transmittance is reduced most significantly for sample #045 which uses coating SolarControl_D on the green body-tinted glass product. Although this level of visible transmittance may not fall below the minimum acceptable value as stated by research by Boyce et al (1995) it will still have a substantial impact on the amount of daylight that reaches the internal environment. Even though the appearance of this coating is clear the reflective characteristic when combined with the green body-tinted glass might provide the most

effective combination of reflectance and absorptance therefore improving the SHGC. Sample #044 is the most effective at achieving a good SHGC value as well as maintaining a higher level of visible transmittance. This coating has a clear appearance so whilst it provides material change to the response of the glazing to solar radiation it does not have a significant impact on the light transmitted within the visible spectrum.

Table 6.10: Comparison of the performance of solar control coatings on clear and green tinted glass within a double glazed unit extracted from *WINDOW*

		Solar				Light
ID	Glazing type IGU: 6mm glass, 16mm cavity (AIR)	<i>T</i>	<i>R</i>	<i>A</i>	SHGC	<i>T_v</i>
041	SolarControl_C on clear + clear	0.3	0.3	0.3	0.4	0.6
044	SolarControl_C on Green + clear	0.2	0.1	0.6	0.2	0.51
043	SolarControl_E + clear	0.4	0.1	0.5	0.4	0.53
046	SolarControl_E on Green + clear	0.2	0.1	0.8	0.2	0.4
042	SolarControl_D + clear	0.5	0.2	0.2	0.5	0.6
045	SolarControl_D on Green + clear	0.2	0.1	0.7	0.2	0.43

With all three glass products both the SHGC and the visible transmittance values decrease when the two aspects of tinted glazing and coating are combined. This suggests that all three combinations reduce the potential for solar gain but also reduce the amount of daylight that will reach the building interior. The solar absorptance sees the most significant change with the values increasing for all three glazing products when applied to the green body-tinted glass. Even though the other performance characteristics are different between products the SHGC values all improve to a value of 0.2 suggesting that they are all effective in terms of solar shading. Although this improves the solar performance of the glazing system providing more control over potential solar gain it also reduces the visible transmittance.

However the SHGC and visible transmittance values generally do not reduce by the same percentage suggesting that there is an element of selectivity in terms of how the glazing systems respond to different parts of the spectrum. The use of these glazing systems often has an impact on the visual comfort of the building occupants, resulting in the likely use of artificial light sources and it could also have a negative effect on the other physiological processes that rely on light stimulus as outlined in Chapter 4.

6.4.3.1 Spectral selectivity of glazing systems

As half the solar radiation falls within the visible spectrum, reducing the total solar transmittance equally across all wavelengths also reduces the visible light available. As shown above altering the material components of glass whether within the sub-base material or the coating material can improve the SHGC by reducing the near infra-red light transmittance of a given glazing system. It will also reduce the visible transmittance but the adjustment of these two values is generally not completely proportional as shown above. This suggests that these treatments for glazing products can provide selectivity in how they interact with different parts of the spectrum. It is therefore possible to maximise the light transmittance of glazing which is primarily specified for solar control by employing spectrally selective components which reduce the transmittance of IR wavelengths whilst maintaining transmittance in the visible spectrum. This is generally most successful when using a coating on the glass.

As described by Correa & Almanza (2004) these coatings are normally grouped into three categories; those using noble metals (copper, silver and gold), metal oxide films and organometallic compounds. Each of these types of coating provides a different selective characteristic to the glass and the light transmitted, reflected or absorbed. It is also often the case that two layers of different compounds are employed to achieve the desired selective characteristic of the glass. Thin copper coatings have been shown to improve the solar control performance of single glazed windows, reducing transmittance of near Infra-red whilst maintaining high visible transmittance (Correa & Almanza, 2004) (Alvarez, et al., 2005). This spectral selectivity means that a good level of daylight is provided for performing visual tasks whilst limiting cooling load as a result of overheating. This is most significant in regions where there are significant periods of high intensity solar illuminance. High performance 'heat mirror' glazing has also been shown to provide 70% more daylight for the same solar heat gain when the area of a window is increased (Littlefair & Roche, 1998). This is achieved by selectively reflecting the parts of the electromagnetic spectrum which cause overheating while maintaining transmittance of a good percentage of the visible spectrum.

The table below shows a range of selective solar protection glass products developed by different manufacturers. Each manufacturer employs different methods and materials to achieve the most effective glazing product for the required outcome. In general there are two main processes for coating glass, on-line and off-line as described above. Each process has different advantages and disadvantages and can affect the performance characteristics of the

product however the off-line coating process is most common in which the glass is coated after the float process once it has cooled.

Table 6.11: Description of a range of selective solar protection glass products from different manufacturers

Glazing name	Coating description	Substrate	Coating side
SpectralSolar_A	metallic oxide – off-line	Clear	#2
SpectralSolar_B	metallic oxide – off-line	Clear	#2
SpectralSolar_C	silver coating – off-line	Clear	#2
SpectralSolar_D	Double layer silver coating – off-line	Clear	#3
SpectralSolar_D1	Double layer silver coating – off-line	Clear	#3
SpectralSolar_E	Thin chemical coating – on-line	Clear	#2
SpectralSolar_E1	Thin chemical coating – on-line	Grey	#2

Most of these coatings can be applied to a range of clear or body tinted glass substrates which will also influence their performance. The table below shows the performance specification of the coatings from Table 6.11 within a double glazed unit. Most of these systems include a clear inner pane except for SpectralSolar_D where the coating is applied to surface #3 (inner face of inner pane) therefore the external pane is clear. The performance of this double glazed system is also compared with one that has a grey body-tinted external pane in sample SpectralSolar_D1. Table 6.12 also includes the light-to-solar gain ratio (LSG) which defines the spectral selectivity of glazing systems by establishing the visible transmittance divided by the solar heat gain coefficient of a given glazing system as outlined by Gueymard (2009). The greater the LSG ratio the more spectrally selective the glazing system is and the greater the reduction in transmittance of the visible spectrum. Defining the LSG ratio in a similar way to Gueymard (2009) will give a picture of the general spectral performance in comparison to the total transmission of each glazing system.

Table 6.12: Performance characteristics of selective solar protection glass products within double glazed units extracted from *WINDOW*

		Solar					Light
	Glazing type 6mm glass, 16mm cavity (AIR) + clear pane unless stated	<i>T</i>	<i>R</i>	<i>A</i>	SHGC	LSG	<i>T_v</i>
047	SpectralSolar_A + clear	0.2	0.5	0.3	0.2	1.7	0.43
048	SpectralSolar_B + clear	0.3	0.3	0.3	0.3	2.0	0.67
049	SpectralSolar_C + clear	0.1	0.3	0.6	0.1	1.4	0.18
050	Clear outer pane + SpectralSolar_D	0.2	0.4	0.2	0.3	1.8	0.61
051	Grey tinted outer pane + SpectralSolar_D1	0.1	0.2	0.6	0.2	1.7	0.31
052	SpectralSolar_E + clear	0.5	0.2	0.2	0.5	1.2	0.6
053	SpectralSolar_E1 + clear	0.2	0.1	0.6	0.3	1.1	0.29

Table 6.12 shows that sample #048, SpectralSolar_B has the highest LSG therefore providing the highest visible transmittance whilst minimising solar heat gain therefore achieving more spectral selectivity. However there are products which perform better in terms of their SHGC rating. Sample #049 using SpectralSolar_C is most effective in terms of solar control with a SHGC rating of 0.1 but this is at the detriment of the visible transmittance which is reduced to 18% resulting in a low LSG rating of 1.4. The silver coating of SpectralSolar_C is a very effective solar protection product but not as successful in terms of spectral selectivity as it also significantly reduces the light transmitted at visible wavelengths.

The thin chemical coating used in SpectralSolar_E, sample #052 seems to maintain a good visible transmittance but is not as effective in terms of solar control and selectivity as some of the other coatings with a LSG rating of 1.2. The performance of sample #050 which has a coating applied to surface #3 of the double glazed unit is similar to that of sample #048 which maintains a high visible transmittance value as well as a good SHGC value. The reflectance value for this glazing system is twice than the absorptance value which may be an effect of the silver component of the coating. With the coating in this position it is important that more light is reflected back into the cavity rather than absorbed as this could result in an increase in temperature of the inner pane of the glazing unit. In turn this heat energy could then be transferred to the internal environment. By adding body-tinted glass as the outer pane of this

double glazed unit the absorptance value also increases as shown in the table above. These two aspects bring the SHGC of sample #051 down to 0.2.

Although the LSG ratio is useful in terms of the describing the balance between solar control and good visible transmittance it does not tell us the specific parts of the spectrum where light is transmitted. In order to understand the potential impact of a given glazing system on the non-visual lighting requirements it will be necessary to also examine the spectral distribution of the light transmitted by a specific glazing system. Using data provided by the *Optics6* software and the International Glazing Database it is possible to get an idea of the spectral power distribution of some of these glazing systems.

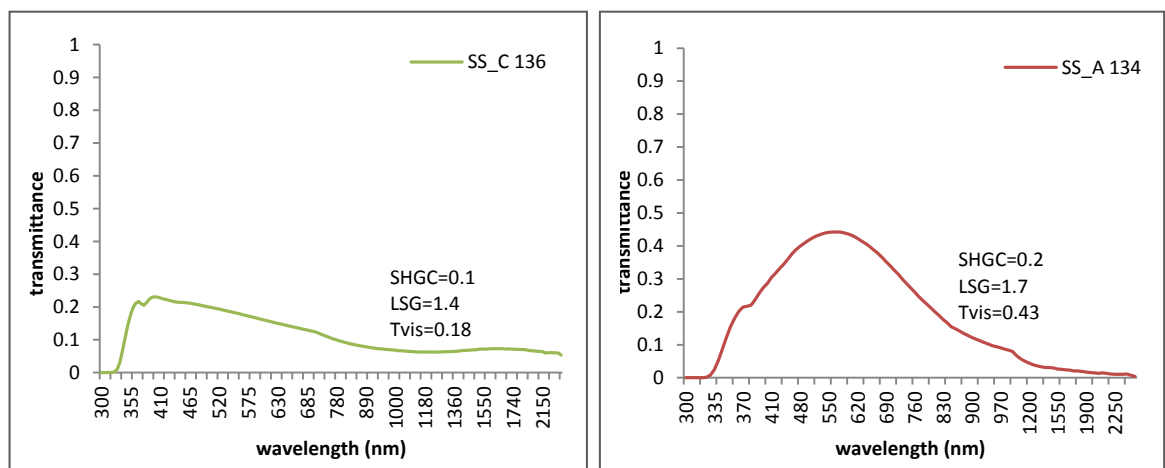


Figure 6.7: Spectral Power Distribution of visible transmittance for glazing samples SelectiveSolar A & C

It is evident from the two graphs in Figure 6.7 that it is not possible to fully understand the impact of a chosen glazing product on the spectral distribution of the light transmitted from the LSG values alone. These two solar control glazing systems perform in substantially different ways. For example although sample #049 transmits more light at the shorter end of the spectrum proportionally to the rest of the spectrum, sample #047 transmits approximately 50% more in the wavelength band proposed as peak sensitivity for the non-visual system, approx 460-480nm. Although this sample may present an extreme example as the total visible transmittance value is extremely low this investigation suggests that the performance characteristics provided by manufacturers may not tell the designer enough about the performance of the glazing system. In particular if it is important to understand the wavelengths of light that are transmitted This could in the long term affect the health of the building occupant based on the amount of light they are receiving within buildings.

6.4.3.2 Glare

A high level of solar transmittance can also cause problems of glare and visual discomfort. Glare can often be a problem in working environments such as offices or school classrooms as it can interfere with the use of computer screens or interactive white boards. Many buildings which are designed to maximise daylight end up not fully utilising this natural resource due to the difficulties of controlling glare and overheating within internal spaces. This is often the reason for internal or external shading devices or blinds to be retrofitted which can often result in the need for artificial lighting to obtain the illuminance levels necessary for visual task requirements.

To improve this performance characteristic it is necessary to reduce the amount of solar energy that is transmitted by the glass or glazing unit. An effective solution for this is to increase the reflectance of the external surface of the glass. This improvement in performance can be achieved by the application of coatings to the glass or by changing the composition of the base material by adding other metal oxides as outlined above. Tinted or coated glazing can reduce glare from the sky and this type of glass has been widely used within office environments but it is less effective at reducing glare from the Sun. The most effective solution for this type of glare is angular selective and daylight redirecting glazing that works by refracting or redistributing the direct sunlight which in turn reduces window luminance.

Although these issues related to visual glare can have a significant on the comfort and productivity of those people affected by them this thesis will not specifically take this design parameter into consideration as it is solely focused on the ability of daylight to provide sufficient light stimulus for the non-visual processes outlined in Chapter 4. There is a seminal study on the issues of glare caused by daylight by Hopkins (1964) as well as ongoing development of research in this area by Osterhaus (2005) and Nazzari (2001).

6.4.4 Combined glazing systems

It is possible to specify more complex systems in which manufacturers have developed combinations of highly efficient or specific coating materials in order to markedly improve the performance of the glass by combining specific characteristics. It is also common to see these combined glazing systems as part of triple or quadruple glazed units being installed into new buildings often where there is a drive towards energy efficiency.

Some of the most advanced glazing systems look to combine highly efficient solar control as well as low emissivity glass products. This combination looks to reduce the overheating from

uncontrolled solar heat gain and therefore the need for artificial cooling whilst retaining what heat there may already be within the interior space. This is often necessary in places where the climate is highly variable throughout the year. This combination of performance requirements can be achieved with either a body-tinted glass with additional coatings or with a series of coatings and films in different positions within the glazing unit. Some manufacturers also advertise glass products which satisfy multiple performance requirements. Getting the combination of these two elements right such that thermal comfort levels are maintained within the internal environment is a challenge; maintaining a good level of transmittance of visible light can sometimes suffer. As the research findings in Chapter 4 have shown, sacrificing the transmittance of visible light for thermal performance could be detrimental when the non-visual requirements for lighting are also considered.

Table 6.13: Performance characteristics of a range of combined double and triple glazing units extracted from WINDOW

ID	Glazing type IGU: 6mm glass, 16mm cavity (AIR)	Solar					Light
		<i>T</i>	<i>R</i>	<i>A</i>	SHGC	LSG	<i>T_v</i>
116	Dble_Combined_A Solar+LowE	0.41	0.2	0.2	0.5	1.2	0.56
117	Dble_Combined_A1 Solar on green +LowE	0.18	0.1	0.7	0.2	2.0	0.4
118	Dble_Combined_B Solar + LowE	0.11	0.3	0.5	0.1	1.4	0.18
119	Dble_Combined_B1 Solar on blue + LowE	0.12	0.4	0.5	0.1	1.3	0.19
120	Dble_Combined_C Solar + LowE	0.34	0.2	0.4	0.4	1.5	0.57
121	Dble_Combined_C1 Solar on green + LowE	0.21	0.2	0.7	0.2	2.1	0.47
122	Triple_Combined_A Solar+Clear+LowE	0.22	0.3	0.3	0.3	1.8	0.48
123	Triple_Combined_A1 Solar on green+Clear+LowE	0.16	0.1	0.7	0.2	2.2	0.4
124	Triple_Combined_B Solar+LowE	0.26	0.1	0.5	0.3	1.4	0.44

The table above shows that a range of performance specifications can be achieved with a combined or advanced glazing system. Some of the samples provide a very low solar heat gain coefficient such as the Dble_Combined B & B1 with the outer pane reflecting or absorbing the majority of the solar radiation. However these glazing systems are not very effective from a selectivity perspective as the visible transmittance is also significantly reduced. The LSG rating for these two systems is quite low at around 1.4 which would probably result in the internal environment appearing quite dull. Sample #116 has the highest visible transmittance value at 0.56 but the light to solar heat gain ratio is one of the lowest as the SHGC is still quite high. By introducing a body-tinted outer pane to this double glazed unit there is a significant improvement in the SHGC to 0.2, a reduction of 60%. This does not result in a similar

reduction in the visible transmittance which only reduces by 30% in turn meaning that the LSG value improves.

Sample #120 has the most balanced performance across all the requirements with a higher visible transmittance than most of the samples in this set whilst maintaining a fairly low SHGC rating. This is also improved slightly when the substrate for the solar control coating is changed to a green body-tinted glass. The LSG rating is increased for this sample #121 as the visible transmittance has not been reduced significantly even though the SHGC has improved with an increase in the solar absorptance. Triple glazed units provide the ability to increase the distance between the outer surface of the external facing pane and the inner surface of the internal facing pan with two cavity spaces. This therefore increases the separation of the internal and external panes of glass which allows them to perform more independent roles; for example the external pane to reduce the solar transmittance either through absorptance or reflectance acting as a primary filter and the inner pane to maximise the visible transmittance whilst also reducing the loss of heat from the internal environment. Therefore this adds a layer of control and manipulation of the performance characteristics of the glazing system and the impact it has on the daylight that reaches the internal environment.

These glazing specifications show that it is important to consider the range of performance characteristics of a chosen glazing system as high performance in one aspect may result in a detrimental effect on another. Glazing systems which are designed to selectively respond to different parts of the electromagnetic spectrum are the most effective in terms of maintaining a high visible transmittance. This relationship defined by the LSG rating needs to be carefully balanced in order for the natural light that is provided within a building interior not only to support the visual system but also satisfies the requirements of the non-visual system outlined in Chapter 4. Although the LSG rating does give a picture of the selectivity of the glass and how much solar radiation is reflected or absorbed in comparison to the visible, it does not tell the designer the parts of the visible spectrum which are transmitted. In terms of the requirements of the non-visual system for which the wavelength of light is important as well as the quantity this rating does not tell the full story. It will therefore be important to also have an understanding of the spectral power distribution of transmitted light for each glazing system.

6.4.5 Switchable glass

Being able to maximise the daylight penetration into a given room interior whilst minimising the solar heat gain or discomfort to the building occupants due to glare is one of the most important challenges faced by building designers when considering facade treatment and daylighting design. The development of glass which can respond to the changing external illuminance conditions, altering the transmittance properties to increase or reduce the amount of light which reaches the room interior would increase the freedom of the designer.

6.4.5.1 Electrochromic glass

Certain materials change colour or opacity when exposed to a small electrical current, by sandwiching these materials between two layers of glass it is possible to create a glazing system which can change the amount of heat and light energy that it absorbs and transmits. Depending on the material used the change can produce a tinted glass or a fully opaque glass with some manufacturers producing products which can provide a range of transmittance values. This can be controlled manually through a simple switch or automatically as part of the building monitoring system (BMS) using information about the external illuminance level provided by sensors integrated into external facade.

This type of glass, which is also described as 'Smart' glass or 'Switchable' glass, is used within the automotive industry such as for rear-view mirrors as well as the building industry internally for partitions as well as externally to reduce solar heat gain and glare. With some products it is possible to provide a change in opacity without the glazing unit becoming fully opaque therefore maintaining a visual connection with the outside. The change in opacity also changes the colour which is often towards a blue tint.

In a presentation at a recent daylighting conference Mardaljevic (2013) reported on a longitudinal study of the performance of an electrochromic glass installation being undertaken within an office environment. This study looked to evaluate the physical performance of the glass as well as the response of the building occupants to assess whether it is a viable option for retrofitting within existing buildings. Understanding the impact of the blue hue on the perception of the people using the space is important as it has been suggested by other studies that this may have an impact on their satisfaction with the space (Arsenault, Hebert, & Dubois, 2012). This study suggests that the direction of view can have a big impact on the perception of colour within the room. If the occupant is facing away from the window the blue hue is often not perceptible. They also tested whether incorporating one clear pane of glass

would provide enough light across the full visible spectrum to further reduce the impact of the electrochromic glass. This seemed to be the case from the anecdotal evidence from those working within the room. Although this raises interesting possibilities for the use of electrochromic or 'smart' glass more studies need to be undertaken to fully understand the impact on the occupant.

Electrochromic glass provides a dynamic approach to daylight control or variable transmission glazing with one of the main benefits being an ability to maintain the view out of the window which is not often the case with other solar control products such as blinds or brise soleil. However electrochromic glass is not yet widely used within the building industry with less than ten electrochromic installations in Europe currently. It is therefore not going to form a part of this thesis.

6.4.5.2 Thermochromic

It is also possible to adjust the properties of a 'smart' glazing system in response to air temperature. This type of switchable glass changes its properties when triggered by ambient temperature of the surrounding environment. The performance characteristics of the glass adjust in order to increase or reduce transmittance.

6.4.6 Other factors

Although this study is not explicitly considering the effect of the specific design of a given window on light availability, we need to acknowledge that there are other factors that need to be considered at this stage. It is evident to most designers that the size and position of the window within the wall or roof are significant factors in determining the amount of light received within the internal space. A number of studies have been undertaken to explore these parameters including a comprehensive study by Rennie & Parand (1998). There are other factors that also directly impact on the transmittance of light.

6.4.6.1 Window assembly

When developing a daylight design and assessing the availability of daylight reaching a given room interior, it is necessary to take into consideration the window assembly. The glazing bars and the frame of a window will naturally reduce the amount of light transmitted; the window assembly can typically account for 10% of the total window aperture when considering a standard window within a wall, the assembly for glazing within roofs and atria could account for more. A series of typical correction factors are defined in BS 8206-2 Code of practice for

daylighting (British Standards Institute, 2008) for a variety of standard window types which can be included in daylight calculations such as average daylight factor.

Using *WINDOW* and *Optics6* software to collect data for a range of glazing systems for this study it was possible to calculate centre of window results. This purposely does not take into consideration the affect of the choice of frame or size of window as this thesis is specifically interested in the impact of the chosen glass and glazing products. It does acknowledge the possible effect of these factors with the wide variety of options both in terms of framing but also window size and position within the external envelope but this is not the main focus of the thesis. In order to make a comparison of the glazing systems on their own it was sufficient to use the centre of glass data at this stage.

6.4.6.2 Dirt and maintenance

The regularity of cleaning and maintenance of windows will also have an impact on the transmittance of light due to dust and dirt deposits. The Building Research Establishment UK (1986) put together a table of maintenance factors for industrial and non-industrial buildings taking into consideration the inclination of the glass and the work that takes place in the building. This publication suggested building in a non-industrial area with vertical glazing in which non-industrial work takes place the maintenance factor is 0.9, suggesting that there will be a 10% reduction to the available light due to dust and dirt on the surface of the window. It suggests that a building in an industrial area that has vertical glazing in which dirty industrial work takes place the maintenance factor would be 0.7 suggesting that there would be a reduction of 30% due to dust and dirt on the external surface of the window.

These conversion factors were based on pre-Second World War studies and as Sharples et al (2001) suggests there have been significant changes since then not least the introduction of the Clean Air Act in 1956 as well as the ban on smoking inside as well as in some public external areas. This study by Sharples et al (2001) undertaken in late 1990s took measurements across 430 windows from a range of building types and functions in order to get a better understanding of the impact of atmospheric attenuation and dust and dirt deposits. The findings showed that the major factors affecting the percentage loss of transmittance were the function of the building, the inclination of the window and the external solar shading/overhang of the window. The average percentage loss in transmittance due to dirt and dust deposition on vertical single or double glazed windows was less than 10%.

A set of recommendations have been developed from these findings to incorporate the effect of urban air pollution on daylight calculations and are included in BS 8206-2:2008 Code of practice for daylighting. It includes a percentage loss of light depending on the particular type of building shown in Table 6.14 as well as multiplying factors for exposure to rain or snow depending on whether the glazing is vertical, inclined or horizontal. Once the relevant values have been chosen for a given location the maintenance factor can be used to work out the reduction of daylight transmittance due to dirt.

Table 6.14: Percentage losses of light in particular types of buildings taken from BS9206-2

Building type	Percentage loss of daylight compared with clean glazing	
	Rural/suburban	Urban
Residential: private and communal. Rooms with few occupants, good maintenance	4	8
Commercial, educational. Rooms used by groups of people, office equipment.	4	8 to 12
Polluted atmosphere. Gymnasia, swimming pools.	12 to 24	12 to 24

This shows that maintenance and cleaning of windows can have a significant impact on the transmittance of daylight into an internal space. It is more significantly affected by the activities that take place within the building than the external air quality but the vertical position and the exposure to weather conditions also have an impact with horizontal glazing being most affected. This is due to the simple fact that dirt is less likely to be washed off and any snow or rain that collects on the glass could also leave debris which could reduce transmittance of light.

6.5 Effect of glazing systems on non-visual light stimulus

As was shown in Chapter 4, the human eye is sensitive to specific characteristics of light which trigger non-visual processes, in particular a different wavelength of light to the visual system. Typical information provided by glazing manufacturers is generally limited to transmittance and reflectance of solar energy and visible light. This gives the designer information relating to the quantity of light that will be transmitted to the room interior as well as the level of solar control and thermal resistance a given system will provide. In order to get a better understanding of whether a specific glazing system will transmit enough light energy to support human non-visual processes it is necessary to have more information relating to the spectral distribution of light transmitted.

A recent study (Bellia, Pedace, & Barbato, 2013) which looked to provide a complete analysis of the effects of daylight and electric light on occupants within a school environment acknowledged the need to further investigate the impact of different types of glass. This study included a predicted melatonin suppression expected from the range of lighting scenarios in the study room in order to get an appreciation of the non-visual impact of the lighting environment. Bellia et al (2013) noted that their study had been undertaken using neutral window glass and that other studies such as the one by Arsenault et al (2012) demonstrate that the colour of window glass may have a significant effect on the arousal level of office workers. They acknowledge that further investigation into the impact of glazing systems incorporating glass that is not neutral would be valuable to ascertain the impact on spectral distributions of light reaching eye level of the building occupant and therefore the expected melatonin suppression.

By looking at the performance characteristics of a range of commonly used glazing types, it is possible to see the varying effects the glazing specification has on the total light transmittance and therefore on the lighting environment within a given room. This would typically be used to establish whether there is enough light for visual perception and performance of task. Chapter 4 provided an overview of the spectral quality of broadband or polychromatic light in terms of its effect on the non-visual system described as *circadian efficient* illuminance by others (Rea, Bullough, & Figueiro, 2002) (Pechacek, Anderson, & Lockley, 2008) (Bellia, Bisegna, & Spada, 2011). This information will provide a picture as to whether this provided enough light to stimulate the non-visual system based on the proposed circadian efficient illuminance calculations described in Chapter 4. However it would also be valuable to understand in a bit more detail the impact of different glazing systems on the spectral

distribution of the light they transmit. This might in turn provide a better understanding of whether certain glazing systems are suitable to stimulate the non-visual system.

6.5.1 Spectral Power Distribution

With the transmittance of light a key factor in the performance of glazing systems the effect of these enhanced glazing systems on the spectral quality of light may not always be fully considered. The industry accepted photometry system focuses on maintaining visual performance which is centred mainly on the quantity of light within a given space. This is exemplified in the use of heavily tinted or coloured glass, often used to reduce solar gain internally and which can create an altered quality of light but still provide the required illuminance levels. The factors described above provide information on the transmittance of visible light for a variety of glazing types with a focus on the quantity of light delivered. The incorporation of the solar-heat-gain-coefficient (SHGC) as well as the calculation of the light-to-solar gain ratio (LSG) gives some indication as to whether there is a spectrally selective characteristic to the glass. However this calculation does not give a clear picture of the full spectral distribution of the light that is transmitted.

If certain wavelengths of light are important to stimulate a response from the non-visual system then it is important to know the impact of the glazing specification on the spectral distribution of light transmitted. As with the artificial light sources described in Chapter 5 some glazing systems may produce a spectral distribution of the light transmitted which is not as effective in support of the non-visual system as others.

6.5.2 Spectral Power Distribution potency for non-visual response

As the research outlined in Chapter 4 shows the human non-visual system has peak sensitivity at a shorter wavelength towards the blue end of the visible spectrum than the visual system. In order to establish whether the different components of a glazing system have an effect on the spectral quality of light transmitted it is necessary to have detailed spectral distribution information for a range of glass and glazing systems. Spectral distribution data has been obtained for this thesis from two sources; through physical measurements undertaken by the author using a FT-IR spectrophotometer as well as using computer analysis software *Optics 6* which uses data from the International Glazing Database. This spectral analysis will provide information as to the amount of light transmitted and absorbed at each individual wavelength band which can be viewed in a similar format as the spectral power distribution (SPD) graphs for artificial lamps.

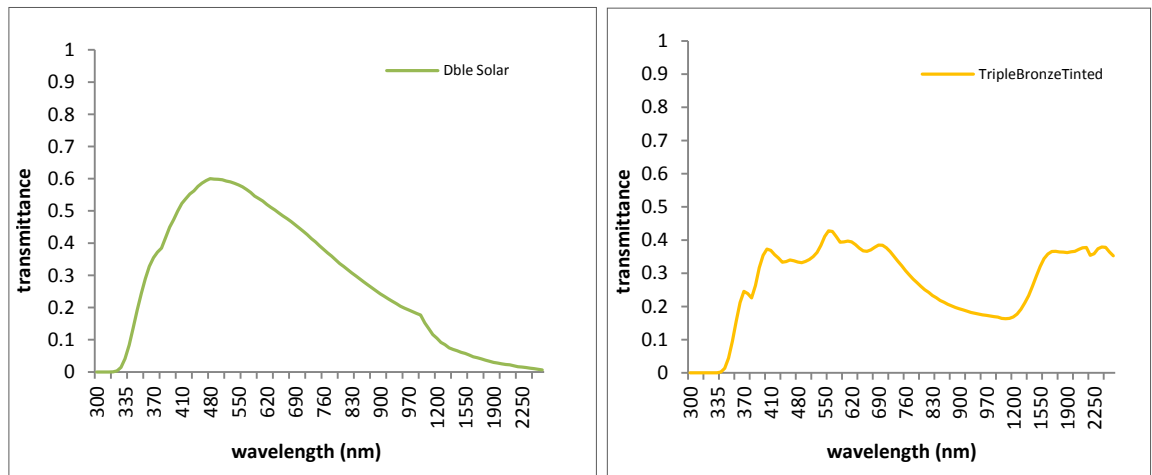


Figure 6.8: Spectral Power Distribution of total transmittance for a Double Solar Control glazing and for a Triple LowE glazing with Bronze external pane extracted from *Optics6*

From this data it is possible to see the effect of a particular glazing system across an extended range taking in visible spectrum and parts of the NIR/ UV spectrum. This provides a picture of the performance of the glazing system in other areas beyond transmitting visible light. This thesis is solely interested in light transmitted within the visible spectrum which is shown in Figure 6.9. From this data it is also possible to establish the percentage transmittance at a specific wavelength or band of wavelengths which would describe in more detail the light that is transmitted at this particular part of the spectrum. It would highlight whether there is a spectrally selective nature of a given glazing system in a particular part of the visible spectrum.

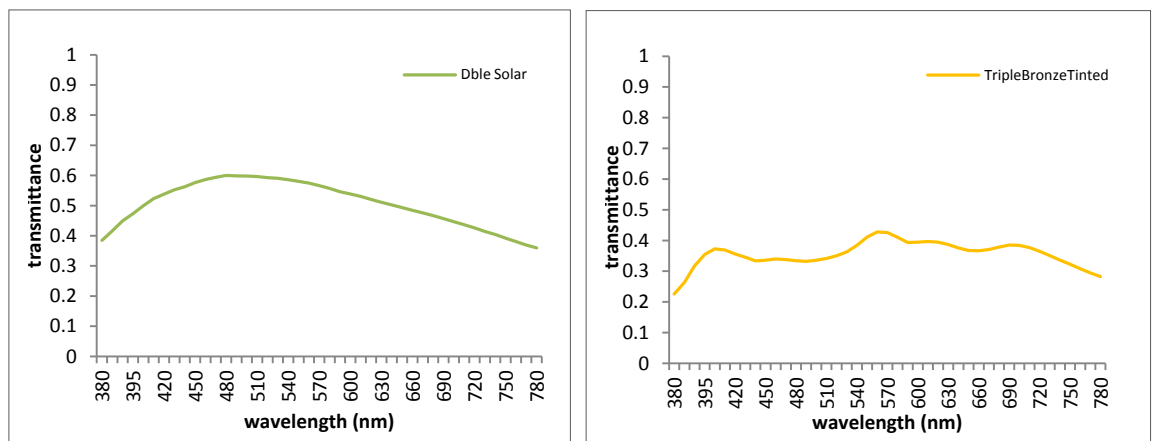


Figure 6.9: SPD of visible transmittance for a Double glazed Solar Control and Bronze tinted Triple glazed LowE unit extracted from *Optics6*

As there is no conclusive agreement as to whether the non-visual system is sensitive to a single wavelength or a range of wavelengths, it is not possible at this stage to accurately define a single wavelength of light that it is necessary for people to receive at their eye. Establishing the effect of a glazing system on a range of wavelengths at the shorter end of the visible spectrum proposed by the research outlined in Chapter 4 would provide a picture of the

potential effect of the glazing on the non-visual process. Taking the range 450-510nm from the detailed spectral information is it possible to calculate the average transmittance across this small band of wavelengths. This will provide a picture as to whether the light transmitted by a particular glazing system includes light at the specific wavelengths important for the human non-visual system and the percentage of the total transmittance.

6.5.3 Effect of glazing characteristics on spectral distribution of transmitted light

As described above the material characteristics of each individual glass and glazing product have an effect on their interaction with light. Glazing manufacturers have developed a series of processes which can alter the inherent material characteristics of glass as a base material whether that is adding other materials or chemical components to the base material or coating the surface in another material. In the sections above these processes were explored in terms of the effect they have on the total visible transmittance, this section will take a brief look at the effect they have on the spectral distribution of the light transmitted.

6.5.3.1 Body-tinted glass

Looking at the spectral distribution of a range of single pane body-tinted glass samples shown in Figure 6.10 it is evident that the different material characteristics have an impact on the spectral distribution of light that they transmit. Clear White glass, which typically has a reduced iron oxide component giving it a much clearer appearance than standard clear float glass which has a green hue, transmits the most light across the spectrum. Looking at the grey and bronze tinted panes they present a more significant reduction in transmittance across the visible spectrum with the introduction of cobalt oxide and selenium oxide being introduced to the base material. The addition of these material compounds into the base material of glass affects the interaction with light at certain wavelengths reflecting or absorbing them rather than transmitting through the material.

Taking into consideration the fact that it is likely that the non-visual system is sensitive to particular parts of the visible spectrum which are different to the visual system it could prove to be significant which parts of the spectrum a glazing system transmits. By establishing the spectral power distribution of light transmitted by each glass product or glazing systems it is then possible to ascertain the amount of light transmitted at certain parts of the spectrum as a percentage of the total transmittance. This in turn will help to better understand the impact of a particular glazing system on the light received by the building occupant which in turn will maintain well-being.

Focusing on the single pane of bronze body-tinted glass for which the spectral distribution is shown within Figure 6.10 below it is possible to establish the percentage transmittance at a specific wavelength. This is shown against the transmittance of a pane of clear float glass in the table below along with the total visible transmittance and the total solar energy transmittance. It is possible to see that there is a reduction in the amount of energy being transmitted at this shorter wavelength in the bronze tinted glazing which is also visible in the spectral power distribution graphs.

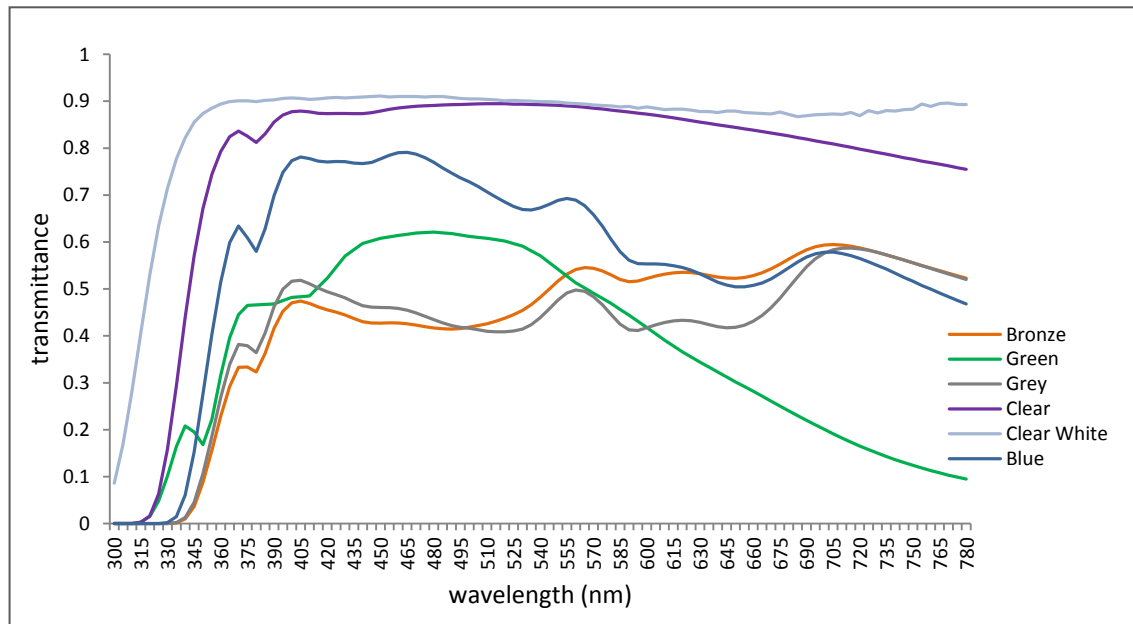


Figure 6.10: Spectral Power Distribution graph of transmittance of a range of different body tinted glass

If the thickness of this single pane of body-tinted glass was increased there is a reduction in the transmittance across the visible spectrum as would be expected. The composition of glass including the addition of selenium oxide has the same absorbtivity coefficient whether its 3mm, 6mm or 8mm thick; it is the pathlength, the distance the light has to travel that has changed. There is a 20-30% difference between the transmittance of a 3mm bronze tinted pane and a 6mm pane across the visible spectrum. Although there is variability across the spectral range between the 3mm and 6mm panes there is a clear similarity in the shape of the graph as is shown in Figure 6.11. The lowest transmittance values occur at the shorter end of the spectrum between 445nm and 510nm which coincides with the wavelength range within which peak sensitivity of the non-visual system has been proposed to fall. This would suggest that a glazing system utilising bronze tinted glass might not be as effective in terms of providing light for the non-visual system.

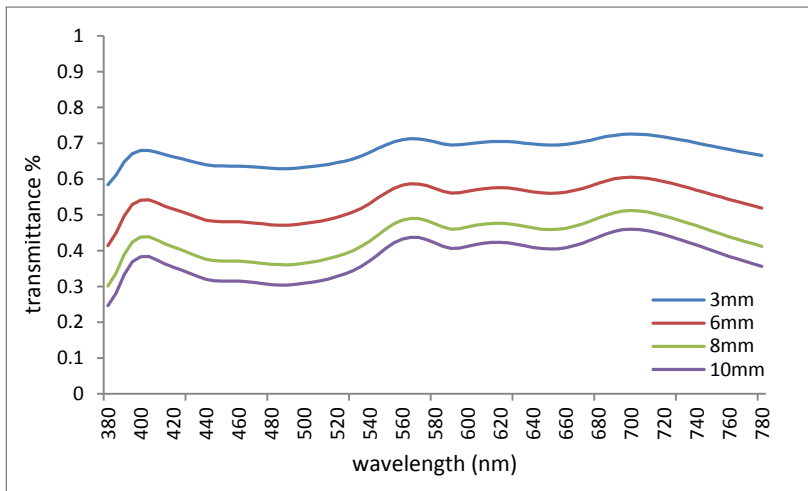


Figure 6.11: Comparison of spectral power distribution of four different thicknesses of bronze body-tinted glass

Table 6.15 shows the total visible transmittance for a series of body-tinted glass samples as well as the average transmittance across the narrow wavelength band described above. For the grey-tinted glass these values are almost exactly the same whereas there is a slight variation with the other body-tinted glass. The bronze glass indicates a slight reduction in the average transmittance value across the narrow wavelength band in comparison to the total transmittance. In comparison the blue-body tinted glass shows an increase within this range in comparison to the total transmittance. This suggests that blue-tinted glass tends to transmit a greater amount of light at this part of the visible spectrum and therefore might present a more effective glazing option to provide light to support the non-visual system.

Table 6.15: Comparison of performance characteristics of different body-tinted glass products including transmittance values at specific wavelength ranges

ID	Glazing type	Light		Solar				LSG
		T_v	Avg T_v across 450-510nm	T	R	A	SHGC	
	Bronze body-tinted							
066	6mm single pane	0.51	0.42	0.48	0.05	0.47	0.8	0.6
067	8mm single pane	0.44	0.37	0.39	0.05	0.56	0.8	0.5
	Blue body-tinted							
071	6mm single pane	0.53	0.76	0.33	0.05	0.62	0.8	0.7
072	8mm single pane	0.42	0.71	0.25	0.05	0.70	0.8	0.5
	Grey body-tinted							
063	6mm single pane	0.44	0.44	0.41	0.05	0.54	0.8	0.5
064	8mm single pane	0.33	0.33	0.31	0.05	0.64	0.8	0.4

6.5.3.2 Glass coating

As described above, coatings or films can be applied to the surface of glass for a variety of reasons. This can be to increase the reflectance of the glass as part of a solar control system or to reduce the transmittance of long wavelength heat energy to improve thermal performance. The exact material composition of coatings for glass will depend on the particular manufacturer. Using *Optics6* software it is possible to establish the spectral distribution of different specialist glass types produced by different manufacturers such as Low-Emittance glass and compare the effect of different manufacturing processes and materials. This comparison is shown in Table 6.16 as well as Figure 6.12 which plots the spectral power distribution of the three Solar Control glazing samples.

Table 6.16: Performance characteristics of different coated glass products based on a single pane including transmittance values at specific wavelength range

ID	Glazing type 6mm single clear substrate	Coating position	Light		Solar				
			Tv	Avg Tv across 450-510nm	T	R	A	SHGC	LSG
021	LowE_A	Back	0.69	0.67	0.26	0.4	0.4	0.5	1.3
023	LowE_C	Back	0.48	0.49	0.29	0.3	0.4	0.6	0.8
024	LowE_D	front	0.77	0.75	0.45	0.5	0.1	0.5	1.5
034	Solar Control_A	Back	0.42	0.47	0.19	0.3	0.5	0.2	1.9
037	Solar Control_D	Back	0.67	0.65	0.46	0.2	0.2	0.5	1.2
038	Solar Control_E	Back	0.6	0.64	0.35	0.1	0.5	0.4	1.4

Looking at both Table 6.16 as well as Figure 6.12 it is evident that the material composition of the coating has an impact on how it performs in respect of the transmittance of light. There is a variation in total visible transmittance of approximately 30% across the three LowE glass samples. This wide variation is a result of the fact that glass sample LowE_C has a silver component which significantly reduces the transmittance value. Table 6.16 also shows that there is only a small variation between the total visible transmittance and the transmittance within the smaller wavelength band across all the samples. Across the three LowE coatings the transmittance values for this smaller range between 450-510nm is generally slightly greater whereas for the SolarControl glass samples it is generally smaller.

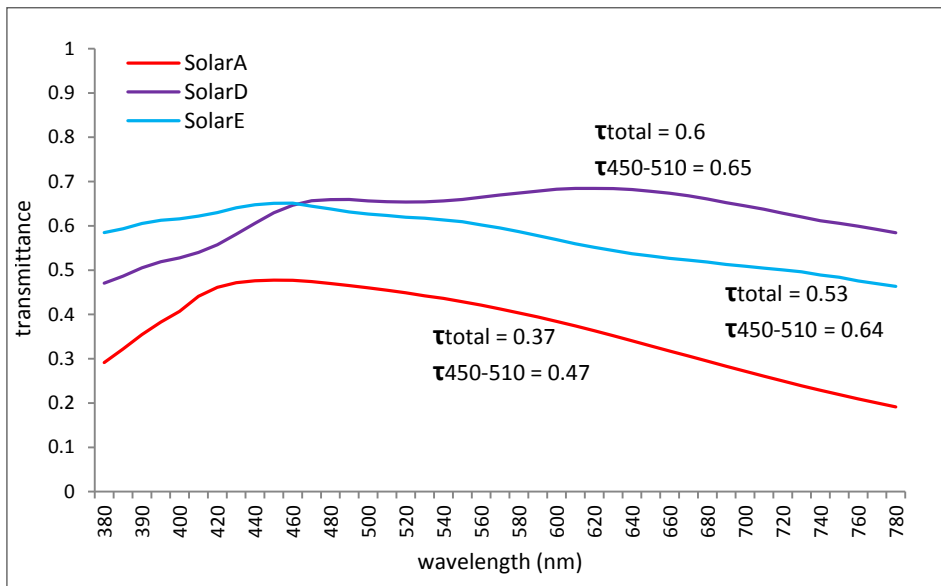


Figure 6.12: Comparison of spectral power distribution of three Solar Control glass samples based on data extracted from *Optics6*

Although it is interesting to compare how these different coated glass samples perform on their own it is very unlikely that any of these coatings would be used on single panes of glass. In most instances due to the delicate nature of the material and the coating process it is more typical for these types of glass product to be incorporated into multi-layered glazing systems which also provide an extra level of protection to the coating material.

6.5.3.3 Multi-layered glazing systems

By incorporating a number of these elements together glazing manufacturers have been able to respond to a variety of requirements for the improved performance of glazing systems. This has mostly been driven by the need to improve energy performance of buildings in general but with particular focus on the building envelope. Although a lot of information about the performance of these glazing systems is provided by manufacturers information about the spectral quality of the visible light transmitted is not typically provided. As the research into the efficacy of certain wavelengths on the human physiological system develops and the evidence as to the spectral sensitivity of the non-visual system understanding the effect these multi-layered, advanced glazing systems have on spectral distribution may become more important.

Undertaking a small evaluation of performing range of glazing systems and the effect they have on the spectral distribution of light transmitted will give a picture of their potential effect on light to support the non-visual system. It may also highlight where certain characteristics conflict with each other. For example solar control glazing products can often be specified to

address discomfort and distraction caused by excessive glare within a space. This type of glass is typically specified for buildings where a uniform light level is needed to support visual tasks and in particular when using visual display screens. This can be common for schools and offices. A highly efficient solar control glass can significantly reduce the total amount of light reaching a space. In some instances where external illuminance is not particularly high it will result in artificial lighting being required where it may not have been necessary. These glazing types could potentially cause a reduction in the amount of light transmitted within the region of the visible spectrum which has been shown to be important as stimulus for non-visual processes. In turn this could have an impact on the well-being of the people inhabiting the space.

The spectral distribution of light transmitted through a range of commonly used and readily available glazing systems from mainstream manufacturers were compared based on data extracted from *Optics6* and is shown below in Figure 6.13. The effect of the different combination of components is evident by the form of the SPD curves for each glazing system.

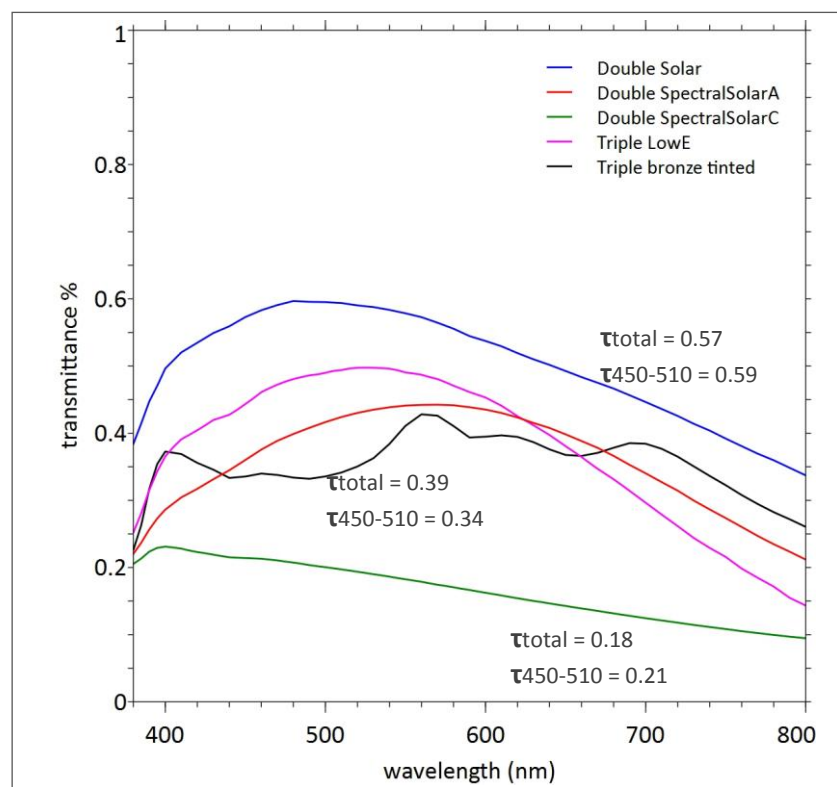


Figure 6.13: Comparison of spectral power distribution of a selection of glazing systems based on data extracted from *Optics6*

With a focus more towards conducted heat and radiant heat loss the development of highly efficient thermal performance glazing through coatings and multiple layers of glass may have less of an effect on the spectral quality of visible light transmitted. Thermal performance

glazing may also incorporate elements of solar control such as body-tinted or reflective coated glazing on the outer pane. The combination of these elements may start to have a small but measurable effect on the spectral quality of light transmitted as proposed by the data derived in Table 6.17.

Table 6.17: Performance characteristics of different coated glass products based on a single pane including transmittance values at specific wavelength range

		Light		Solar				
ID	Glazing type	T_v	Avg T_v across 450-510nm	T	R	A	SHGC	LSG
056	Double Solar Control	0.57	0.59	0.3	0.2	0.4	0.4	1.5
039	Double SolarSelectiveA	0.43	0.4	0.2	0.5	0.3	0.2	1.7
041	Double SolarSelectiveC	0.18	0.21	0.1	0.3	0.6	0.1	1.4
098	Triple LowE	0.48	0.48	0.2	0.3	0.3	0.3	1.8
104	Triple Bronze tinted	0.39	0.34	0.3	0.1	0.5	0.4	1.1

Highly efficient thermal performance glass is most often used in colder climates where heat loss can be a problem. These areas are also potentially those where the available external illuminance can be low at certain times of the year such as the winter months in the most northerly parts of the Northern hemisphere. If the glazing used is reducing both the total light transmittance as well as that within the shorter, blue end of the spectrum effective for the non-visual system it could have a negative effect on the buildings occupants.

6.6 Summary and conclusions to Chapter 6

The window or glazing system is the threshold between the outside and the inside of a building. It presents a filter for daylight before it penetrates an internal space therefore having an impact on the quantity and quality of light that reaches the building occupant. It performs a fundamental role within the building envelope however, it is also one of the worst performing building components available to designers in terms of thermal resistance therefore affecting the energy efficiency of the building.

Development of glazing systems has therefore focused mainly on thermal performance as well its ability to limit solar heat gain. Glazing manufacturers have tried to develop systems that maintain visible transmittance guided by recommendations for the optimum lighting environment for the human visual system. These systems might transmit enough light to stimulate visual response but they have not been designed to take into consideration the non-visual response to light stimulus as described in Chapter 4.

As shown above, Double glazed units designed to respond to solar gain have a greater impact on the total transmittance of visible light. It is considered that the energy and financial implications as a result of overheating within building interiors make the reduction of solar gain a priority. However over-design of solar shading and solar control glass can be a common occurrence and result in a reduction of daylight received by the building occupant.

To see significant improvements in either solar control or thermal resistance properties of glazing systems it is necessary to combine a number of components such as coatings or films as well as multiple layers of glass. Further advancements in material technology have meant that glass coatings can be manufactured so that they interact with certain parts of the visible spectrum in different ways. Ultimately the use of these products means a noticeable reduction in the total visible transmittance as can be seen in the data above.

As lighting guidance is currently driven by the human visual system and the ability to perform visual tasks there is an emphasis on the quantity of light provided. As it has been shown by previous research the building occupant's perception of how much light there is within an internal space is often affected by the light source, therefore the quality of light as well. If a different quality and quantity of light is proven to be needed to support non-visual processes this may not be achieved if the total transmittance of glazing is significantly reduced.

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Chapter 7

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7 Initial evaluation of the impact of glazing

This Chapter will look at the effect of the specification of the glazing system on the light that reaches the inner surface of the glass based on the available external illuminance of a range of geographical locations. This will give an initial understanding of its ability to provide adequate light intensity at the correct time of day for the stimulation of non-visual processes.

The performance of glazing systems is generally described by the percentage transmittance of light within the visible range as well as other performance statistics for solar heat gain and thermal resistance. Representation of the performance of glazing systems in this manner is a response to the required data input for calculation of energy performance of a given building facade to a certain degree. More importantly the representation of total light transmittance responds to the fact that the current system of photometry is derived in direct relationship to the performance of the human visual system (Boyce, Eklund, Magnum, Saalfeld, & Tang, 1995). It is currently only necessary to determine how much light reaches an interior space to support visual tasks rather than other performance characteristics that might support the non-visual system.

As highlighted in Chapter 4 the spectral quality and quantity of light received by the eye is also important to the stimulation of non-visual responses. Unlike the visual system, these non-visual responses to light are specifically affected by the time of day light is received at the eye. Non-visual responses to light such as circadian-resetting are directly connected to the time of day at which light is received at the eye, more sensitive in the early morning or early evening. This suggests that as well as the total transmittance values of the chosen glazing system the availability of external illuminance will affect the suitability of a glazing system in a specific location. This availability will be affected by the time of year and local climate as discussed in Chapter 5. Using this information it is possible to establish whether the necessary quantity of light will be transmitted to stimulate certain non-visual responses such as circadian resetting.

At this stage this analysis will look purely at the effect of the glazing system not taking into consideration the size and shape of the window or the design of the room. This will simply establish the light that reaches the inner surface of the glazing system. It has been assumed that the glazing system is sat within a building that is not surrounded in close proximity by any other buildings or tree cover which would significantly absorb or reflect external illuminance. It is acknowledged that this is not a realistic scenario for many building contexts but necessary to make an assessment of the glazing system in isolation.

7.1 Glazing sample range

Based on the series of glass and glazing types analysed in Chapter 6 a smaller sample series was put together which could be used to investigate the impact of specification on the light that is transmitted to an internal space. A range of six different glazing systems were chosen from the more extensive glazing sample matrix included in Appendix A and created using *WINDOW6* software which draws on optical data provided by the International Glazing Database (IGDB). This smaller selection of glazing systems represents a range of standard glazing types typically used in the construction industry and available from mainstream glazing manufacturers. It was also important that the visible transmittance values of these glazing types were varied providing a range of performance characteristics.

A maintenance factor was also applied to the transmittance values as set out in BS8206-2:2008 (British Standards Institute, 2008). This value assumes that an amount of dirt and debris will collect on the surface of the glass in-situ. The British Standard sets out a range of multiplying factors based on the context or setting of a building such as whether it is rural or urban as well as the building function such as residential, commercial or educational. These correction factors are multiplied together to provide an overall maintenance factor which in essence will be a reduction of the transmittance value from 100%. Based on the assumed conditions of the hypothetical context a maintenance factor of 0.88 was applied to the transmittance values of each of the glazing systems as shown in Table 7.1.

Table 7.1: Performance characteristics of glazing sample series

Sample	Glazing Type	Tvis	Rfvis	Tsol	SHGC	LSG	Overall Tvis (Tvis*M Factor)
1	Double LowE	0.61	0.1	0.23	0.2	2.5	0.54
2	Double Solar Control	0.57	0.12	0.34	0.4	1.5	0.50
3	Double blue tinted	0.48	0.08	0.28	0.3	1.6	0.42
4	Triple LowE	0.48	0.26	0.22	0.3	1.8	0.42
5	Triple blue tinted +LowE	0.4	0.11	0.21	0.2	1.6	0.35
6	Triple bronze tinted	0.39	0.11	0.3	0.4	1.1	0.34

7.2 Total transmittance analysis

Chapter 4 outlined three methods by which circadian efficient illuminance levels can be derived as developed by other researchers (Pechacek, Anderson, & Lockley, 2008) (Bellia, Bisegna, & Spada, 2011) (Anderson, Mardaljevic, & Lockley, 2012). These methods are based on suggested action spectra of non-visual processes such as melatonin suppression and circadian phase-resetting. Through an analysis of the advantages and disadvantages of each of method for use in this thesis outlined in Table 4.5, method #3 based on research by Bellia et al (2011) was selected. By establishing a circadian action factor Bellia et al were able to derive the circadian efficiency factor of a range of light sources including daylight. Using the assumed thresholds summarised in Table 4.2 this method offers an opportunity to propose a range of circadian equivalent illuminance levels necessary to stimulate the human non-visual processes. It is then possible to establish whether the transmittance values of certain glazing systems are sufficient to provide enough circadian efficient light within a building interior to stimulate these non-visual responses.

Chapter 5 also outlined the changeable nature of daylight and defined a picture of the available external illuminance levels of three different latitudinal locations based on climate data from *SATELLIGHT* (SATELLIGHT, 1997). Using the total visible transmittance values for a range of glazing systems set out in Table 7.1 and the monthly mean of hourly external illuminance values for these three locations it is possible to calculate the potential illuminance level received at the inner face of a given glazing system. Although these figures must be seen as estimates at any specific instant in time, it offers an understanding of the effect of a chosen glazing specification on the light available for the building occupant. By combining this assessment with a set of assumed light requirements proposed from the research in Chapter 4 such as timing, duration and light intensity it is possible to establish whether any glazing system from the sample range is not effective in providing the necessary light stimulus by natural means. It will also identify whether attention needs to be paid to particular locations or times of year, or with a glazing system used in a specific orientation or vertical surface.

7.2.1 Non-visual illuminance thresholds

To assess the success of this range of glazing systems to support the human non-visual system assumed lighting requirements were used for two non-visual responses known to be connected to light stimulus received at the eye; circadian resetting and subjective alertness. The research outline in Chapter 4 suggests that the lighting parameters for each response are slightly different particularly in relation to the timing of light received. Research indicates that

there is a non-linear correlation between illuminance level and both immediate and phased physiological responses to light exposure. This therefore suggests that there could be slightly different illuminance thresholds for each non-visual response. A brief overview of both non-visual responses and the proposed lighting requirements is given below.

7.2.1.1 Circadian phase-resetting

Research has shown that circadian phase-resetting or phase-shifting has a non-linear dose-response to light intensity such that 100lux achieved a half maximal response in comparison to 10 times the illuminance which was needed to achieve a maximal response (Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). Although the findings suggest that the non-visual system requires a higher illuminance than the visual system there is some uncertainty as to the exact illuminance levels needed. Therefore it seems plausible to assume a range of illuminance values within which a response could be expected. This is further supported by research which has shown that there is a relationship between illuminance level and length of exposure resulting in an effect on the level of stimulation (Khalsa, Jewett, Cajochen, & Czeisler, 2003).

The time of day which light stimulus is received has been shown to be significant to the impact on phase entrainment as described in Chapter 4. For example the phased response to light of the sleep/wake cycle is particularly sensitive to light exposure in the early biological night as well as the early morning. Further studies have suggested that the circadian system is controlled by a dual oscillator, one diurnal and one nocturnal, that are entrained to dawn and dusk respectively (Wehr, Aeschbach, & Duncan Jr, 2001). This mechanism has been shown not to be connected therefore people might respond to light stimulus in the evening and in the morning differently.

This suggests that the light received by a building occupant during the early hours of the day could have an impact on their circadian phase irrespective of light exposure in the evening. In terms of the application of daylight within the built environment this thesis considers that the early morning is a significant time during which exposure to light stimulus is most potent to building occupants. The assumption is that light received between 06.00-10.00 has the most potent effect on the circadian phase entrainment, advancing or resetting to the day/night cycle of the local context. The monthly mean of hourly illuminance levels received on the internal surface of a given window system were viewed in respect of this part of the day.

7.2.2 Subjective alertness

A connection between light stimulus during the day and an increase in subjective alertness has also been identified by researchers (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003) (Vandewalle, et al., 2006). This is also supported by a number of studies of productivity in the workplace which show possible correlation between daylight and alertness and concentration (Heschong Mahone Group Inc, 2003b) (Aries, Veitch, & Newsham, 2010). Although there needs to be further investigation in this area research to date has shown that the quantity of light received is positively correlated to an increase in daytime alertness therefore emphasising the importance of providing interior lighting environments which support non-visual processes.

Research outlined in Chapter 4 suggests that there is a strong connection between the quantity of light needed and the time of day it is received. To be able to design a space which provides the appropriate environment for non-visual processes, the ability of the occupant to maintain alertness could be significant particularly when considering specialised or high-risk tasks. As well as the quantity of light received, the time of day is also important similarly to circadian phase-resetting. Research outlined in Chapter 4 suggested that this response to light is most sensitive between the middle of the day and the afternoon.

As was outlined in Chapter 4, Table 7.2 provides a summary of the proposed lighting characteristics to support these two non-visual responses to light.

Table 7.2: Graphs showing available external global illuminance for Helsinki during winter and summer months based on data extrapolated from *SATELLIGHT*

Non-visual response	Intensity		Timing	Duration
	Lower threshold	Upper threshold		
Circadian phase-resetting	370lux	800lux	Early subjective morning 06.00 – 10.00	2 hours
Subjective alertness	200lux	840lux	Subjective day 12.00 – 17.00	1-2 hr

Each of the six glazing samples will be assessed based on the external available illuminance from a specific geographical location based on the performance requirements of these two non-visual responses. Based on the assumed dose requirements set out above the total transmittance illuminance levels for all four vertical orientations were analysed based on season and time of day.

7.2.3 Geographical location

The external illuminance data extrapolated from *SATELLIGHT*, as discussed in Chapter 5, for vertical illuminance in four orientations will be included at four times throughout the year; Summer assumed as June, Winter assumed as December and the season shoulders defined as September and March. This data has been evaluated for three locations across a range of latitudes in the Northern hemisphere: Helsinki, Paris and Tangier. Only Helsinki will be discussed here, for the evaluation of the other two locations refer to Appendix C.

7.2.3.1 Helsinki

As might be expected of a location such as Helsinki in Finland at latitude 60°10N the availability of daylight changes quite dramatically throughout the year. Winter months in particular offer very low levels of external illuminance across an average day. The length of daylight hours during a 24 hour period varies significantly between the seasons with on average 19 hours in June and July, in comparison to only 7 hours on average in December and January. The difference between maximum illuminance levels during an average day in June and that of December can be seen clearly in the two graphs in Figure 7.1**Error! Reference source not found..**

During a winter's day based on global illuminance levels, which include direct light from the sun, it is only the south facing facade that would be expected to receive close to 10,000lux. At this time of year there is very little light available at the other vertical surfaces throughout an average day. This in turn means that if the chosen glazing system reduces visible transmittance by even a small amount the illuminance level within the building interior will be significantly affected. This extreme range of potential external illuminance throughout the year increases the complexity of ensuring that the design and specification of a building facade maintains an optimum internal illuminance level across all seasons.

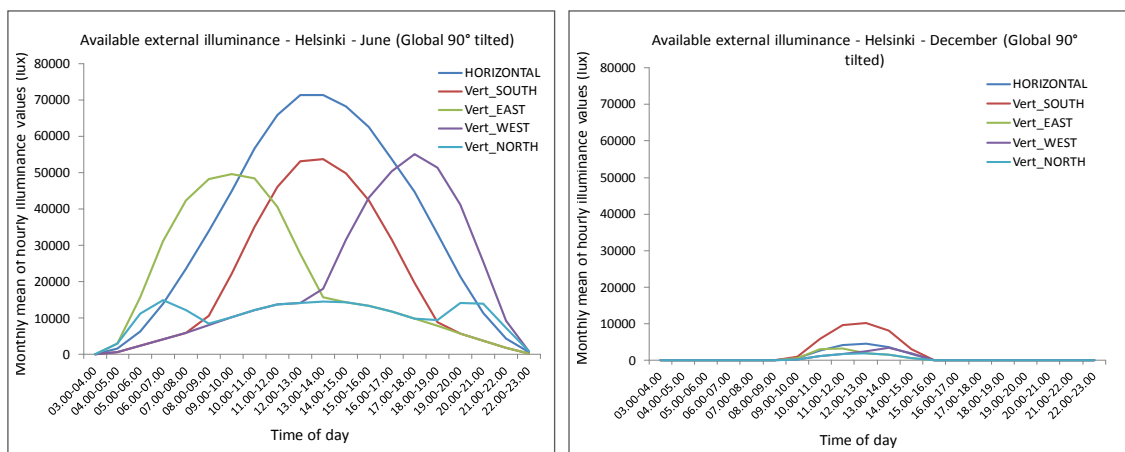


Figure 7.1: Graphs showing available external global illuminance for Helsinki during winter and summer months based on data extrapolated from *SATELLIGHT*

Based on these data for mean hourly illuminance levels for each month at each vertical surface, it is possible to see the impact applying different glazing systems has on the potential illuminance level transmitted to an internal environment. Figure 7.2 provides a good representation of the variation based on orientation of facade and available external illuminance when examining the potential transmitted illuminance levels for an East and North facing facade. They both provide fairly short periods of daylight overall with none of the glazing systems on either facade achieving a transmitted illuminance level of over 2000lux. For the North facing facade only the Double LowE glazing system achieves an illuminance level over 1000lux. Only this glazing system and the Double Solar Control system would achieve both lower and upper illuminance thresholds for the non-visual responses described above at any time in an average day.

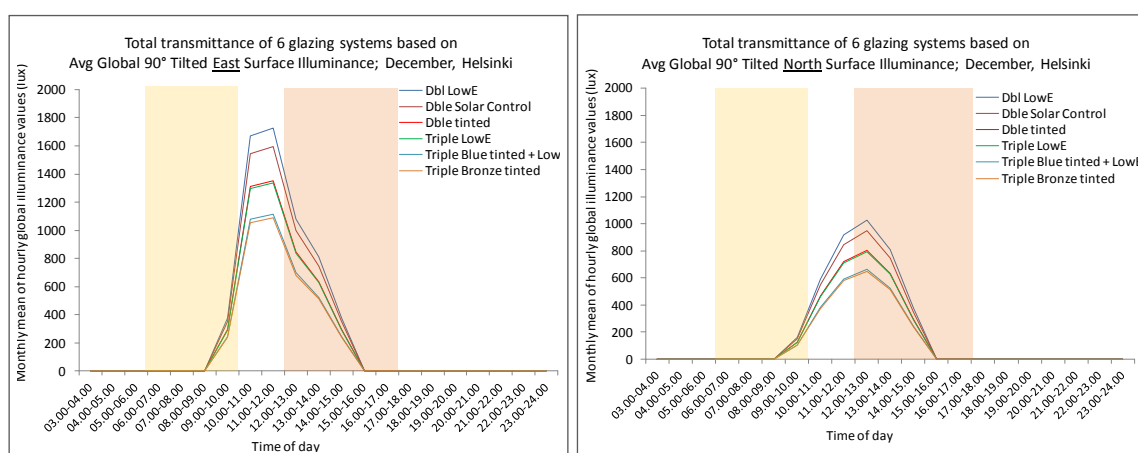


Figure 7.2: Total transmittance of 6 glazing systems based on external global illuminance for an East and North facing vertical plane in December in Helsinki showing two periods of day most effective for non-visual response; 6-10am and 12-5pm.

Research has also suggested that when considering light stimulus for non-visual responses one of the most important factors is timing. For example, even though the human biological clock has an innate day/night cycle, research outlined in Chapter 4 suggests that light stimulus in the early biological day can advance or delay the circadian phase. If this external illuminance data is analysed based on the period of the day most effective for stimulating these non-visual responses it starts to emphasise further the impact of these extremes of daylight availability.

As shown in Figure 7.2 above, for the East facing facade the upper illuminance threshold for stimulation of circadian phase-resetting is not achieved until the very end of the period of the

morning when this non-visual system is most sensitive. Analysing the same data for a vertical surface facing North shows that none of the six glazing systems would provide illuminance levels which reach the lower or upper threshold during this period of the day. This may be expected for a north facing facade in December at latitude of 60°N.

Focusing on the period of the day between 12-5pm, also highlighted in Figure 7.2 that has been suggested as most effective to stimulate alertness, the illuminance thresholds are slightly easier to achieve. Although East and West facing vertical surfaces provide very low levels of transmitted light during Winter months, all six glazing systems will provide illuminance levels to achieve both lower and upper thresholds during this period of the day. This is shown in more detail for the East facing facade in Figure 7.3. However, on the North facing facade only the Double glazed LowE (sample #1) and Double glazed Solar Control (sample #2) systems will provide enough light to achieve the upper illuminance threshold of 840lux. The lower threshold of 200lux would be achieved by all the glazing systems during this period of the day.

It is important to note that these illuminance levels only represent what might be expected to be measured if a light meter were placed at the inner surface of the glazing system therefore not taking into consideration the inter-reflection of light around the internal space. This evaluation is therefore the best case scenario in terms of light received within a hypothetical internal space. Realistically the light received by a person within this space is likely to be significantly lower.

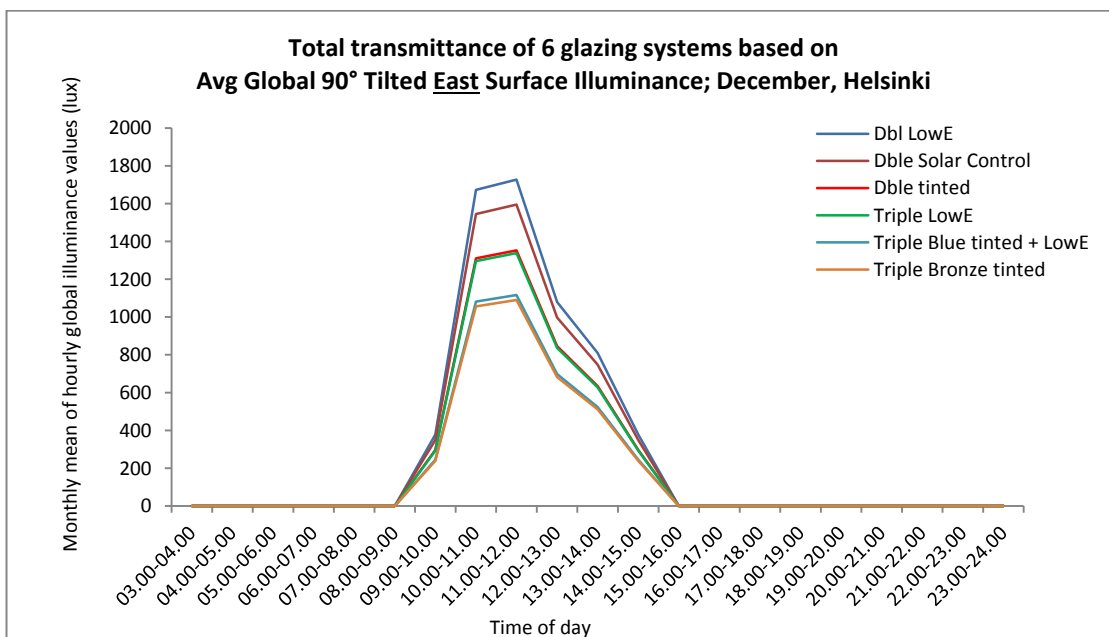


Figure 7.3: Total transmittance of 6 glazing systems based on average global vertical illuminance for December in Helsinki extrapolated from SATELLIGHT

Figure 7.3 through to Figure 7.6 highlight that the effect of glazing choice is most apparent for vertical surfaces facing North where throughout the year glazing systems such as sample #5 or #6 (body-tinted Triple glazed systems) transmit illuminance levels from 600-5000lux across an average day. Glazing sample #4 (Triple Glazed LowE) transmits illuminance levels from 800-6000lux, with the highest transmittance, that of the glazing sample #1 (Double Glazed LowE) only reaching between 1000-8000lux throughout an average day. For vertical surfaces facing South the visible light transmitted is significantly higher, between 3500-29,000lux throughout the year across the range of glazing systems based on global illuminance levels. This shows that for a south facing facade it is likely that a glazing system chosen with a visible transmittance value between 0.61–0.39 will transmit the necessary quantity of light to support both non-visual response.

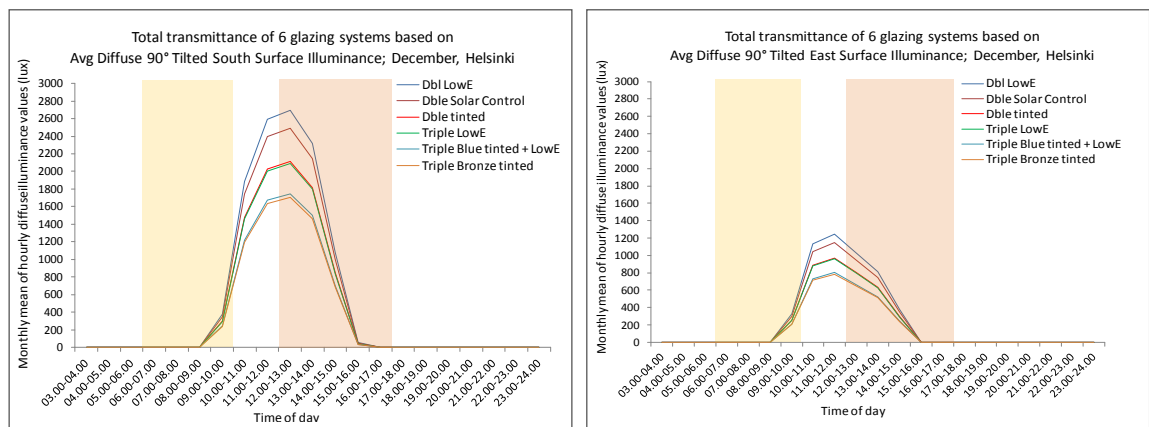


Figure 7.4: Total transmittance of 6 glazing systems based on external diffuse illuminance for a South and East facing vertical plane in Helsinki showing two periods of day most effective for non-visual response; 6-10am and 12-5pm.

Looking at the results based on diffuse vertical illuminance values a more balanced distribution of light availability across an average day is provided with less significant peaks. There is also an overall reduction in illuminance level as would be expected. The maximum transmittance across an average day during December for a south facing facade would not reach above 1700lux for Triple Glazed Bronze tinted system or 2100lux for Triple Glazed Blue tinted system, both triple glazed systems with a tinted outer pane. The maximum illuminance level reached using glazing sample #1 (Double LowE) is 2700lux throughout the day as shown in Figure 7.4. The illuminance levels transmitted to the interior space would be enough to achieve lower and upper thresholds for circadian phase-resetting as well as alertness but the shortened daylight hours mean that these illuminance levels would only be achieved between 9-3pm. Although this period of time would support subjective alertness it would be unlikely to provide the necessary light stimulus for circadian phase-resetting.

These illuminance levels are further reduced when looking at an East facing facade. Based on the orientation only four of the glazing systems (samples #1 – #4) provide illuminance levels over the upper threshold for both non-visual responses across the day. Although all the glazing systems will provide illuminance levels to achieve the lower threshold this is unlikely to be achieved during the early-mid morning, the critical time of day to support circadian phase-resetting.

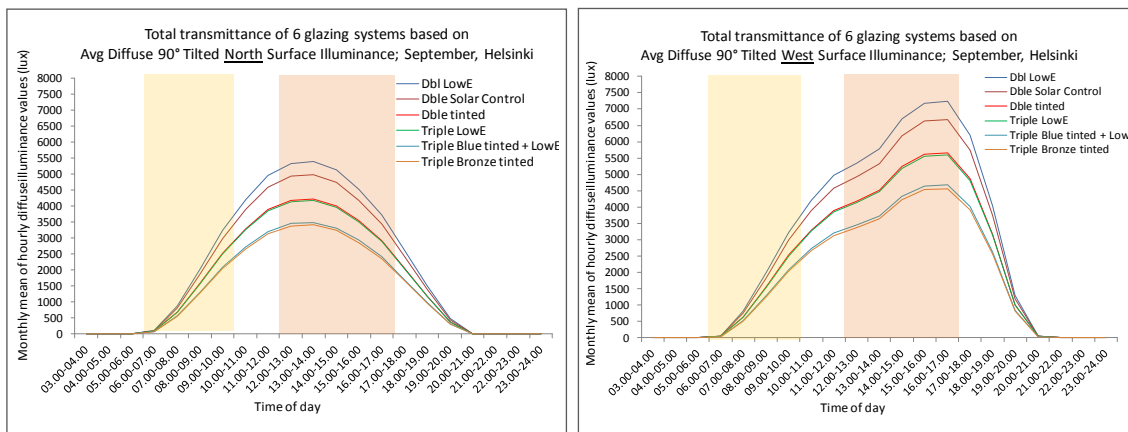


Figure 7.5: Total transmittance of 6 glazing systems based on external diffuse illuminance for a North and West facing vertical plane in September in Helsinki showing two periods of day most effective for non-visual response; 6-10am and 12-5pm.

Analysing the average diffuse illuminance levels on an average day in September based on a vertical surface facing north shown in Figure 7.5, although they rise above the upper threshold for stimulation of circadian phase-resetting they are still low. The maximum illuminance achieved during the early-mid morning is approximately 2000lux for glazing sample #6 (Triple glazed Bronze tinted) and approximately 3000lux for the glazing sample #1 (Double LowE).

There are similar results for the illuminance levels achieved by the West facing vertical surface in September. As the graph in Figure 7.5 shows the majority of light received through the west facing facade occurs during the mid to late afternoon, an effect of the position of the sun relative to this particular vertical surface. As would be expected this shift of higher illuminance values towards the afternoon will effectively support the stimulation of subjective alertness with all glazing systems providing well over both lower and upper threshold values. Overall these graphs show that rooms facing both North and West may be less effective in supporting circadian phase-resetting during the early-mid morning than they are in supporting subjective alertness in the afternoon.

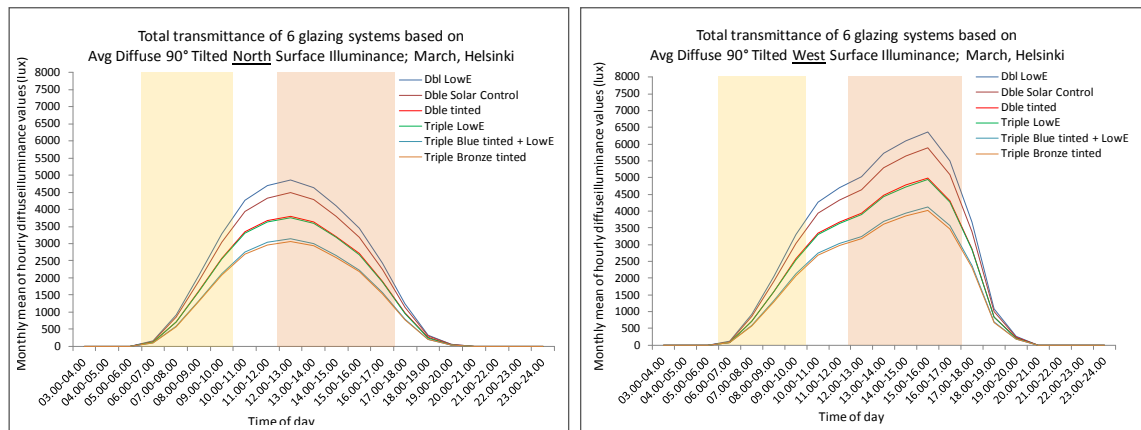


Figure 7.6: Total transmittance of 6 glazing systems based on external diffuse illuminance for a North and West facing vertical plane in March in Helsinki showing two periods of day most effective for non-visual response; 6-10am and 12-5pm.

A similar situation is shown for an average day in March in Figure 7.6. The maximum illuminance values in this period of the morning between 6-10am for a north facing vertical surface are approximately 2250lux for Triple Glazed Bronze tinted system, 3000lux for Triple Glazed LowE and 3800lux for the Double Glazed LowE system. These values exceed both the lower and upper thresholds for the circadian phase-resetting from about 8am in the morning onwards. Although these values seem sufficiently high to stimulate the non-visual processes as outlined above, these values describe the light level at the inner surface of the glazing system and would be expected to reduce significantly at points further into the room.

The diffuse illuminance levels achieved on both North and West facades reach both proposed lower and upper thresholds for the stimulation of alertness between 12-5pm. The illuminance levels achieved during this period of the day on the inner face of the west facade vary between 4000-6500lux depending on the choice of glazing system. In comparison, on the north facing facade the illuminance levels range between 3000-5000lux for this period of the day.

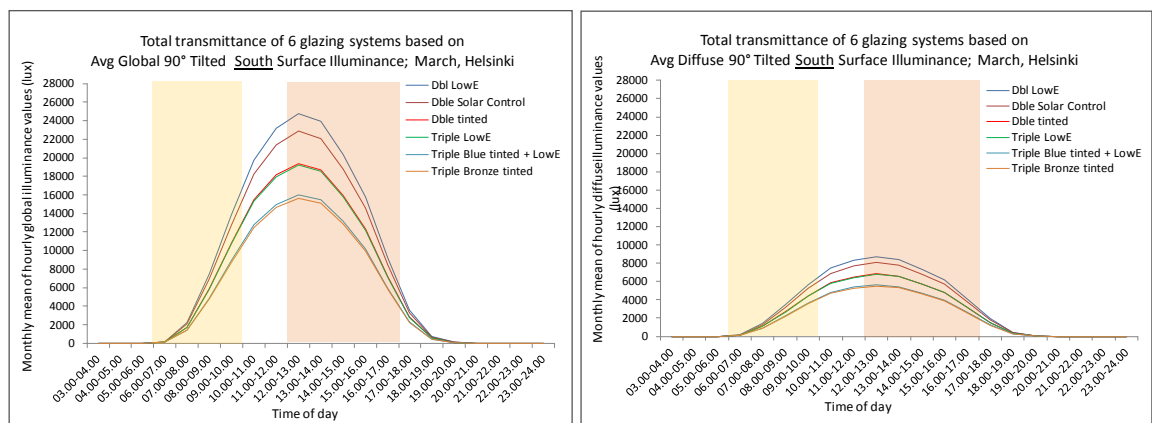


Figure 7.7: Comparison of total transmittance of 6 glazing systems based on external global and diffuse illuminance for a South facing vertical plane in March in Helsinki showing two periods of day most effective for non-visual response; 6-10am and 12-5pm.

Looking at the south facing facade in more detail Figure 7.7, with the exception of the winter months this facade receives the highest illuminance values. This might be expected but the impact of the direct light from the sun is particularly emphasised when looking at the transmitted illuminance levels compared to those based on average diffuse illuminance. The south facing facade generally provides enough light at the inner surface of the glazing system to reach the threshold for circadian phase-resetting during the early-mid morning with the exception of December. However, it is evident that if glazing systems were specified to respond to the high illuminance levels received from a clear blue sky with direct sun they may present a problem during the times of the day or month when the sky is overcast. Looking at the two graphs in Figure 7.7 shows that a triple glazed system with a body-tinted external pane would offer significantly reduced internal light levels.

7.3 Summary and conclusions of Chapter 7

As is evident by the transmittance values for visible light across the range of glazing samples included in this evaluation there is a difference of approximately one third transmittance between sample #1, Double Glazed LowE, with the greatest transmittance value and sample #6, Triple Bronze tinted, with the smallest. However based on global transmittance across a full day most of these glazing systems would appear to provide enough light to support non-visual processes.

As outlined in Chapter 4, the timing of light has been shown to be important for non-visual processes. When taking this factor into consideration there are a number of instances, based on this set of glazing samples, in which providing the illuminance necessary to achieve the proposed threshold to stimulate circadian phase-resetting would be unlikely. This is in part due to the time of day that light is most effective for this non-visual response. The reduced daylight hours at this latitude and in particular during the Winter months means that there is a significant percentage of the year when there are extremely low illuminance levels during this period of the day. Even during the Spring the illuminance level may not reach above the upper threshold until a third of the way through this effective period of the morning.

In comparison it is likely that there will be enough light during the middle of the day to support the stimulation of subjective alertness for all glazing systems throughout the year with the possible exception of the winter months, due to the shortened daylight hours. The choice of glazing system will have an impact on the illuminance level at this time of day but not to any significant amount.

The findings above also show that in order to satisfy the illuminance levels necessary to support circadian phase-resetting it will be important to carefully consider the orientation of spaces within a building. Those spaces that will be occupied during this early to mid morning period of the day should be located towards the south or easterly facing facades. This could have implications for the orientation of the dwelling as a whole as well as the position of rooms such as the bedrooms. Optimum orientation will maximise the potential external illuminance available but at this latitude it is likely that there may be periods of the year when this illuminance threshold is not sufficiently met by daylight irrespective of orientation.

Although these results suggest that this range of glazing system would provide enough light in the majority of circumstances it does emphasise the implications of the specification of glazing based on location and orientation as well as the time of day light stimuli is required. The

Double glazed systems provided the highest illuminance values transmitting enough light to achieve the illuminance thresholds for both non-visual responses, with the exception of the North facing facades in the winter months. This would have been expected based on their visible transmittance values however it is increasingly common to see Triple Glazed systems installed in new buildings particularly in colder climates to provide better thermal efficiency. These systems have been shown to have a measurable impact on the internal illuminance levels and therefore an ability to provide enough light to stimulate non-visual processes. If Triple Glazed systems which include coatings or films, to enhance thermal performance or solar control, are chosen then careful consideration of orientation and available external illuminance will be needed.

The function of the building and the activities that take place within it are always a factor in the implications for any new lighting environment. Research outlined in Chapter 4 has shown that to support the non-visual system the specific time of day that an activity takes place will also need to be considered. This thesis has shown so far that there will be a direct relationship between when certain activities take place, the internal arrangement of buildings based on the available external illuminance and the lighting requirements for the non-visual system.

Overall the results of this initial study have shown that all the glazing systems would provide enough light to stimulate both circadian phase-resetting and subjective alertness if the majority circumstances. However as was noted at the beginning of the chapter this study was limited to an analysis of the amount of light that reached the internal face of the glazing system. Although this has identified the implications of the variability of daylight throughout the year and the effect of different facade orientations when combined with a range of glazing systems it only establishes the light a person might receive if they are standing up against the window looking out. In order to provide a more accurate picture of the amount of light that would reach the eyes of a person within a space it is necessary to look at the effect of the room behind. The next Chapter of the thesis will look to build on this Chapter in the context of a Case Study room.

Chapter 8

Case Study

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8 Case Study

In order to understand the full effect of the choice of glazing system on the light that reaches a building occupant it is necessary to evaluate this within an actual room interior. Chapters 8 and 9 use physical measurements and modelling of an existing room, assessed as if it were in 3 different geographical locations, to provide a Case Study of the varying effects of different glazing systems on the light reaching the eyes of users within this room. This particular Chapter initially looks at the Case Study room independently of location.

Chapter 7 established the impact a particular glazing system has on the available daylight based on a geographical location and time of day or year. However, the amount of light actually reaching the eyes of an individual occupant of a room will also be affected by the design, layout and choice of materials and finishes within the room.

Whilst the focus of this thesis is not to specifically look at the effect of varying room designs on the lighting environment, it is important to establish the effect of different glazing systems on the light received by the building occupant within the context of a room, to establish the relative importance of various parameters in this light distribution.

8.1 Room design

There are a number of design guidance documents to support the design of buildings which maximize occupant comfort within internal spaces, and in particular with daylight penetration. A good example of this is the document produced by the Building Research Establishment (Rennie & Parand, 1998) which provides a series of design tables which show how the adjustment of certain aspects of a room such as the ceiling height, depth and window position and area can affect a variety of environmental factors within the room, including daylight levels. Figure 8.1 gives an example of this design tool. In terms of daylight it gives the average daylight factor across the room depending on various parameters of the building, as well as adjustment factors such as percentage of visible sky and average reflectance values of the internal surfaces of the room. This provides an estimation of the daylight provision across a given room on a horizontal plane.

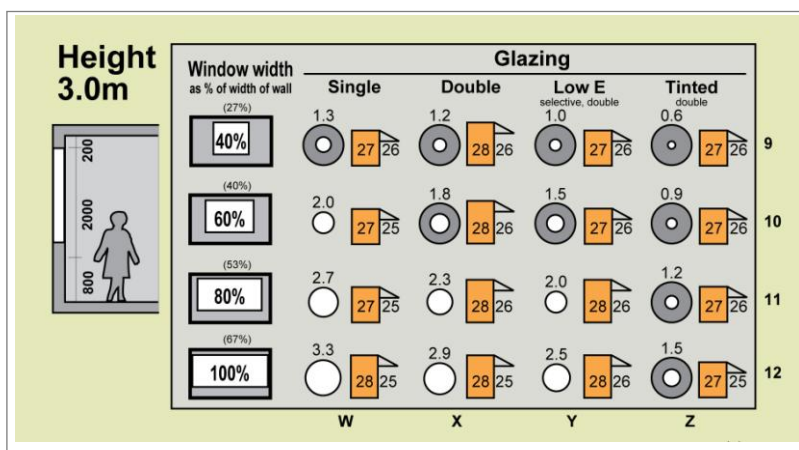


Figure 8.1: Example of design table from Environmental Design Guide (Rennie & Parand, 1998)

In terms of the light stimulus that is received by the building occupant it is important to understand how the distribution of light varies across a given room, as the position of the occupant within the room normally means differing amounts of daylight will be available. It is possible to assess this daylight variation for a particular internal space either physically or virtually using a computer model. This thesis uses both methods to assess the daylight availability at various geographical locations, within a physical room design and layout at Cardiff University. This testing provides the means to establish the effect on the amount of daylight reaching the eye by varying a range of attributes of the room, both physically and within a calibrated model of the room.

A teaching room facing north-northwest was chosen on the first floor of the Bute Building, a large three storey building on the Cardiff University campus, as shown in Figure 8.2. It has two large windows in the exterior wall with the depth of the room, and therefore the furthest point from the window, being approximately 7.6m with a floor area of approximately 42m². Although a suspended ceiling had been installed the ceiling height was still high at 3.7m with the window head height being higher than this at 4.7m within a bulkhead at the window. Taking into consideration the suspended ceiling, the 8m² window area is approximately 60% of the total external wall area, well above the recommended window area for a room which is restricted to windows in one wall (CIBSE, 2012). The existing windows within the room are very slender, clear, double glazed units within a series of medium sized panes. The window frame was white painted metal with an opening light within the lower section of the window.



The interior design of the room was relatively simple and typical of a teaching/seminar room environment with light coloured walls and a dark carpet on the floor as shown in Figure 8.3. The furniture within the room was set up in a traditional arrangement for a seminar or teaching session with six desks facing an interactive whiteboard on the wall farthest from the windows. In this scenario it is most likely that the people in the room would sit facing away from the windows towards the whiteboard but it is also possible that this space could be used in a different configuration with the occupants facing in different directions.



Figure 8.3: Photographs of Case Study room facing whiteboard and window wall

8.1.2 Physical measurement of light levels

Physical measurements were taken at four positions within the room based on a typical seating arrangement used within this space. This was done in order to establish the impact of the seated position of a person over the depth of the room, as shown in Figure 8.4.

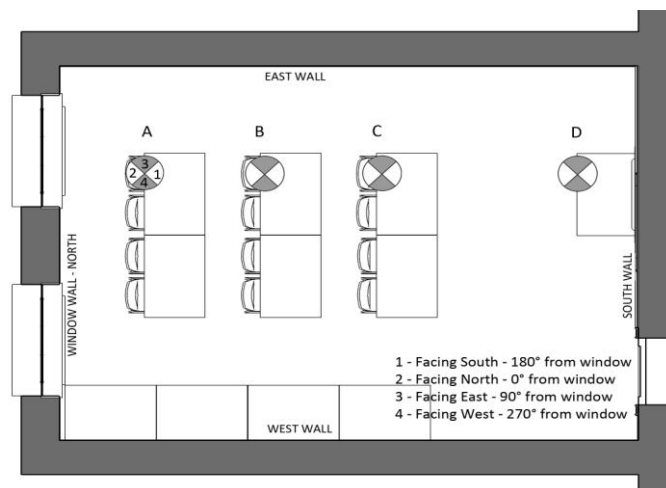


Figure 8.4: Plan of Case Study room showing four light measurement positions

These chosen seated positions were on the same linear axis across the depth of the room. This linear axis was also slightly offset from the centre line of the room in order to establish the impact of the proximity of a person to a wall surface on the vertical, as well as the horizontal, illuminance level. As the envelope of the room was symmetrical based on a centre line taken from window wall across the depth of the room measurements in this part of the room would provide an overview of the distribution of light across the whole space.

A series of measurements were taken at each of these positions within the room, as shown in Figure 8.6, to ascertain the light distribution at different distances from the window. A horizontal illuminance measurement was taken on the desk surface. To ascertain the amount of light that would be reaching the eye level of the occupant at these four internal positions, apparatus was also set up in

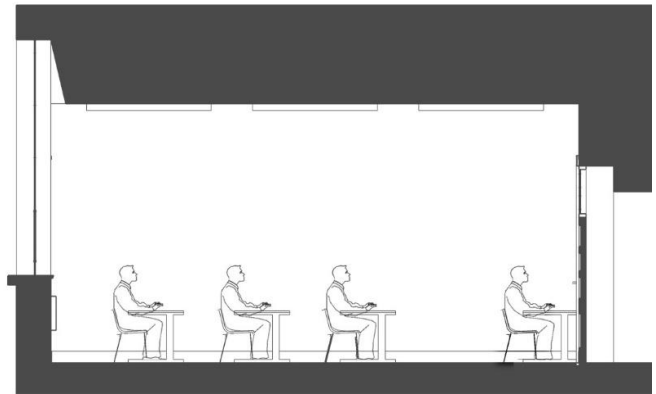


Figure 8.6: Section through Case Study room showing seated positions

order that a consistent measurement of vertical illuminance could be taken at a height of 1200mm from the floor, the assumed eye level of a seated person based on the furniture within the room as shown in Figure 8.5. It is also possible that the amount of light that reaches a person's eye will be affected by their direction of gaze, the direction in which their head is facing. This is something that can change on a regular basis during the time spent within a room presenting a potentially large variable in the light levels receive at the eye (Bierman, Klein, & Rea, 2005). At each seated position within the room a series of vertical illuminance measurements were therefore taken in four azimuth orientations, these were described as north (facing the window wall), south (facing the teaching wall), east and west (facing the adjacent walls).



Figure 8.5: Light measurement apparatus

As well as the vertical illuminance measurements taken at 1200mm to simulate the eye level of a person in a seated position with an angle of gaze 90° to the horizontal desk surface, it was also likely that a person would spend a percentage of their time looking at a visual task on the desk. In order to establish the amount of light reaching their eye if their angle of gaze was downwards toward the desk, another measurement was taken at a 45° angle from the vertical at each position within the room. This follows on from guidance set out in Chartered Institute of Building Services Engineers Guide A to Environmental Design as well as others which highlights the affect of field of view of a person working on a visual task on a horizontal plane

(CIBSE, 1999) (CIBSE, 2012) (Kosir, Krainer, Dovjak, & Kristl, 2011) (Bellia, Pedace, & Barbato, 2013).

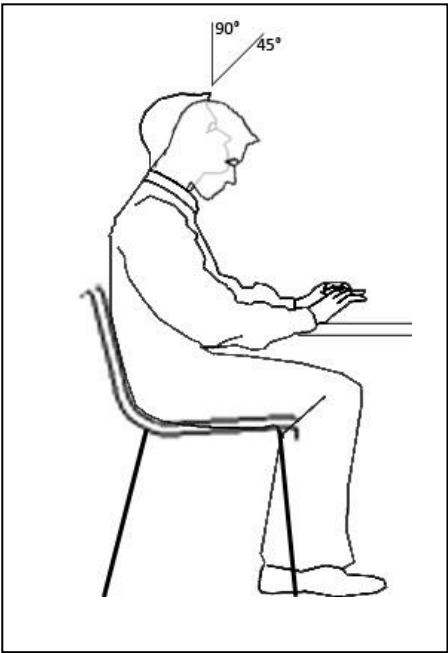


Figure 8.7: Diagram showing 90 + 45 degree measurement positions

By taking measurements at both vertical (90°) and 45° this establishes the effect the angle of a person’s head might have on the light received at the eye. In order to replicate a potential working/studying environment a white piece of paper was placed on the desk in the position the measurements were being taken. This change in colour and therefore reflectance on the horizontal surface has an impact on the amount of light reaching the photosensor, and was designed to represent the best available amount of light in this situation, so that the data was conservative when coming to any conclusions about light availability.

For each seated position within the room 9 separate measurements were taken, an example from the dataset is shown in Table 8.1. The measurements at each position within the room were taken simultaneously with individual lux meters; one on the horizontal plane and at the chosen eye position (90° or 45° from horizontal). The photometer used to take the light level readings at the assumed eye position was a Minolta CL-200A Chromo meter and all other light meters used were calibrated to this light meter. This calibration process is described in more detail in Appendix D.

Table 8.1: Template of the range of measurements taken for each position within the Case Study room

Position in room	Horizontal	Vertical (90°)				45°			
		North	South	East	West	North	South	East	West
A									

8.2 Horizontal vs Vertical daylight distribution

Although there are new approaches proposed to establish daylight distribution within building interiors (Nabil & Mardaljevic, 2006) (Mardaljevic, 2008) (Iversen, Svendsen, & Nielsen, 2013) (Mardaljevic, Anderson, Roy, & Christoffersen, 2012), there has not yet been universal acceptance of these methods and full incorporation into lighting standards. As highlighted by a recent article by Tregenza (2014) there is a long term place for simple measures such as the Daylight Factor, a method currently used by architects to establish effective daylight distribution. This is considered to be due to its simplicity to use and value in providing a good correlation between theory and practice in terms of the daylight distribution within space. As this thesis is concerned with testing the hypothesis that choice of glazing system can affect the physiological regulation processes connected to the eye, maintaining a direct relationship between measured light levels at the eye and the amount of light available externally was important. The use of Daylight Factor therefore seems the most appropriate measure for this investigation.

As described in Chapter 2, the Daylight Factor is a simple ratio of the internal illuminance at a point within the space to the simultaneously available external illuminance. In order to establish the distribution of daylight throughout an internal space it is possible to establish daylight factor values for a grid of positions (CIBSE, 2012). This typically involves taking horizontal light measurements at regular intervals within the space at a chosen height, whether this is at floor level or more typically at desk or work surface height. This simple exercise establishes the amount of light falling on the working plane within the room and the change in light distribution around the room expressed as a percentage of the external light level. Although this method only provides relative values in reference to the light that is available outside, it does establish the success of a particular design in providing daylight throughout an internal space. It can also help to ascertain whether the room requires supplementary artificial lighting to satisfy visual comfort in order that the inhabitants can perform visual tasks. This is why the measurements are typically taken on a horizontal (working) plane.

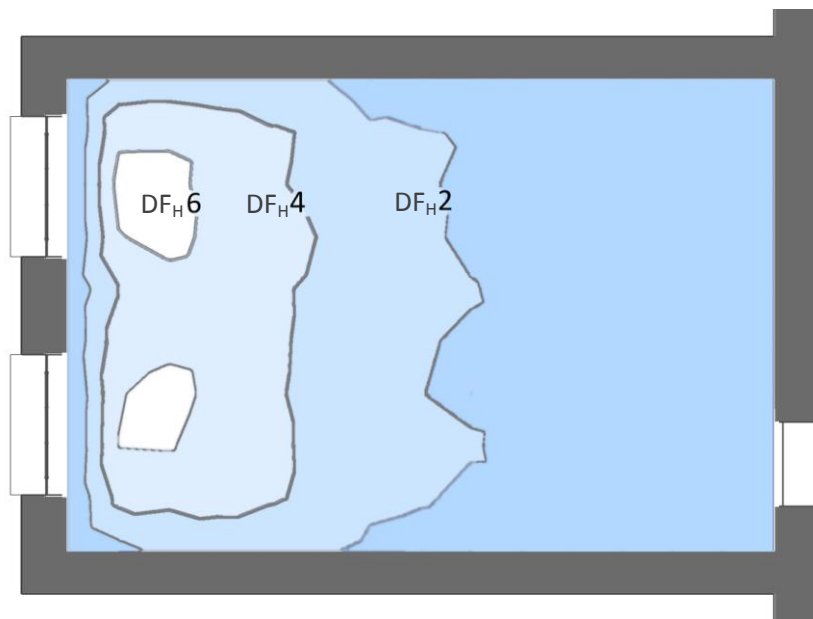


Figure 8.8: Horizontal DF contour plan of Case Study room

Figure 8.8 shows a daylight factor contour plan created for the Case Study room to establish the distribution of light throughout the space using a horizontal measurement position at desk height. Typically the further the position within the room is from the window the greater the drop-off in illuminance, so it is also possible from these measurements to ascertain the reduction in daylight reaching the horizontal plane available across the depth of the room. This is shown quite clearly in Figure 8.9 by overlaying the section of the room with a graph plotting the horizontal DF values at increasing depths from the window wall.

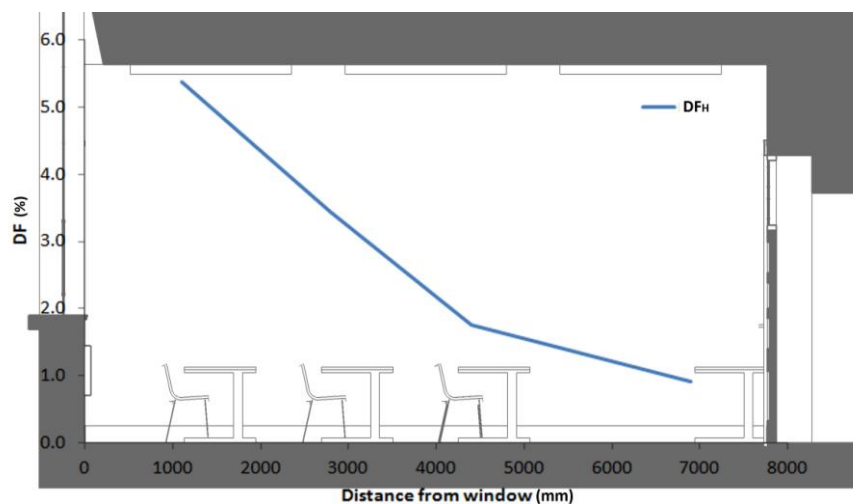


Figure 8.9: Graphical representation showing the change in DF across a section of the Case Study room

The findings in Chapter 4 highlighted the importance of the light that is received at the eye and the connection with other physiological processes within the body beyond the visual system. It is therefore important to determine the amount of light that reaches the eye of an individual

person inhabiting a particular room. This suggests that the standard method for taking horizontal measurements at the height of the working plane would not provide the necessary information. It would be more relevant to take vertical illuminance measurements at an approximate eye height of an individual within an internal space, a method used in a recent study by Bellia et al (2013). Using a simple ratio such as the daylight factor based on a vertical surface within a room could be as valuable as the horizontal daylight factor and understanding the relationship between the two could be quite significant as shown in Figure 8.10.

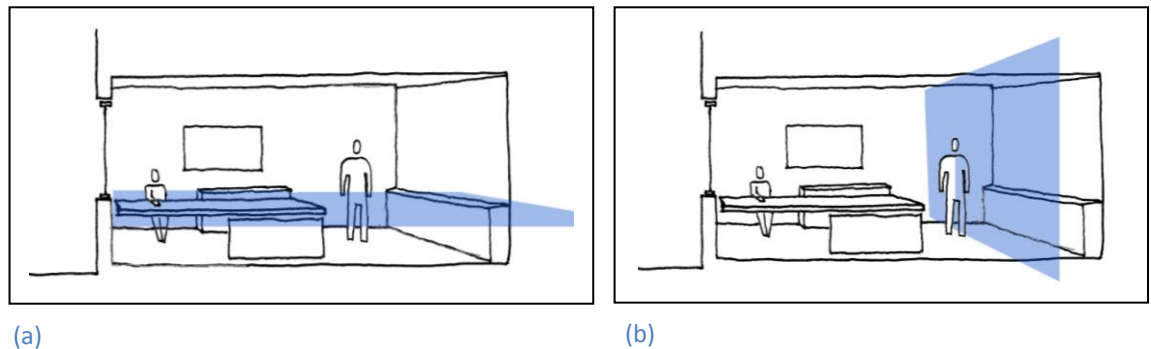


Figure 8.10: Graphical representation of (a) horizontal and (b) vertical illuminance planes

8.2.1 The relationship between Horizontal and Vertical Daylight Factor

Both Horizontal and Vertical Daylight Factors were compared in this study to try and understand how much light was available at the eye. Initially a comparison of the Horizontal Daylight Factor (DF_H) and Vertical Daylight Factor (DF_V) values at the four positions within the Case Study room was made, with the assumption that an individual would be sitting facing away from the window. This is shown in Figure 8.11 as a section through the space from the window to the back of the room. It highlights the difference between the available light in horizontal and vertical planes at different depths within the room. Both these measurements were taken without anyone in the seated position so as to establish the amount of light reaching that particular point within the room without people providing any physical obstacles, therefore representing the best case scenario.

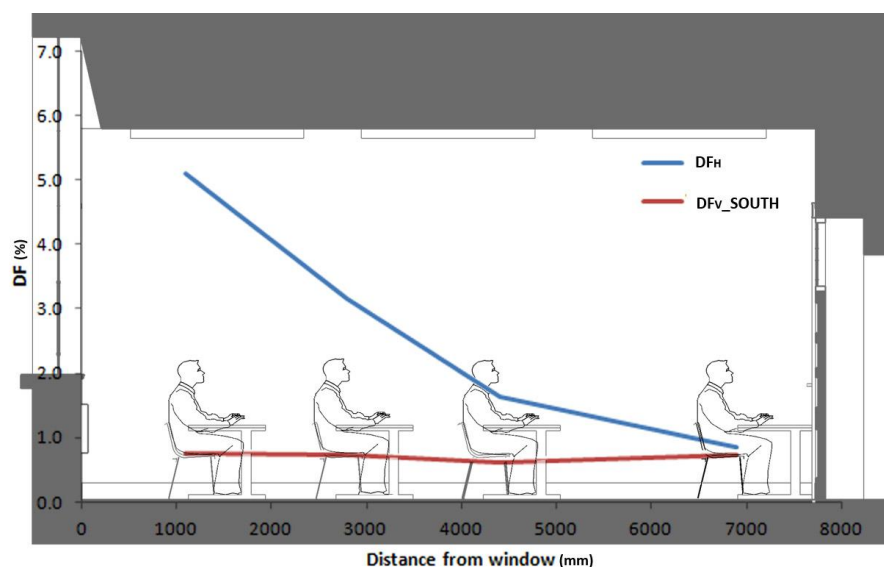


Figure 8.11: Graphical representation showing a comparison of horizontal and vertical DF values across depth of room (occupant facing 180° from window)

The vertical illuminance levels are shown to be uniformly low across the room when the vertical plane is facing 180° away from the window, with the greatest difference between the two values evident nearest the window. The light reaching the vertical plane is predominantly reflected light from the surrounding surfaces, whereas the horizontal surfaces are also receiving direct light from the window. This is the reason that the difference between the two is most significant at the position nearest the window. The DF_V value is 85% less than the standard horizontal DF value at this position. The DF_V values remains consistently low across the depth of the space, only varying by approximately 15%. This highlights that if a person was facing away from the window wall the light reaching their eyes would not vary significantly irrespective of how far they were from the window.

Looking at a similar graph but this time showing a comparison between the Horizontal Daylight Factor (DF_H) and the Vertical Daylight Factor (DF_V) from the position of a person facing the window there is again an obvious difference, as shown in Figure 8.12. As might be expected, in this case the DF_V values were greater across the depth of the room than those on the horizontal plane. There is less of a difference between the two values at position A nearest the window with the vertical DF value being just over 25% greater than the horizontal DF value. This would be expected as the light sensor was facing directly towards the window therefore receiving a large amount of direct light.

This direct light component helped maintain a high DF_V value across the room such that there was not such a sharp drop off in comparison to the horizontal DF value. The difference

between the two values increased to over 60% at point C which is approximately 4.5m from the window. Beyond this point in the room there was a more significant drop-off in illuminance level and by the furthest point in the room the difference between the two values was approximately 50%. The overall conclusions are that if a person was sat facing the window within this room they would expect to receive between 30-170% more light at their eye than would be recorded at the horizontal desk surface.

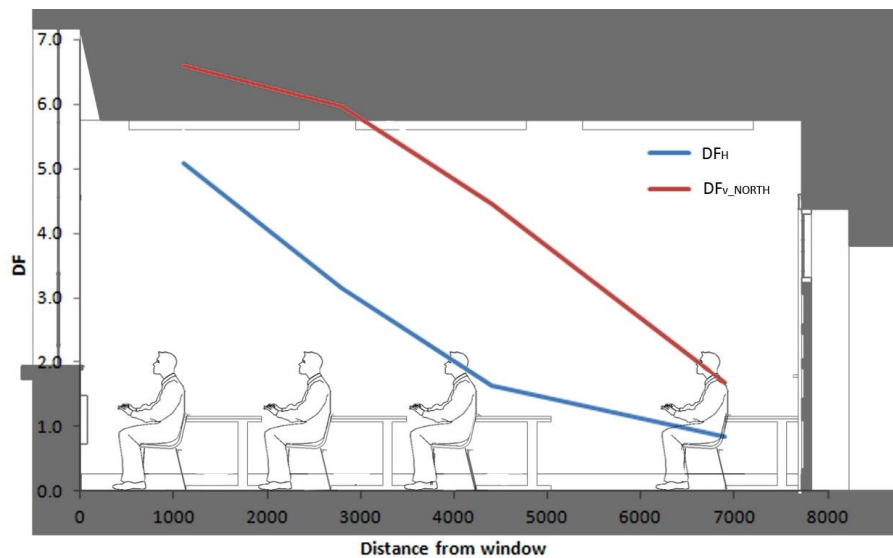


Figure 8.12: Graphical representation showing a comparison of horizontal and vertical DF values across depth of room (occupant facing window)

The difference between the set of Vertical DF values obtained from facing the window, shown in Figure 8.12, and those obtained from facing away from the window, represented in Figure 8.11, highlights the impact that the position of the occupant within a room has on the light that reaches their eye. As this Case Study room is single aspect (a window in only one external wall) the orientation (the direction) a person is facing has a significant effect on the amount of light that might be received at their eye.

Taking these two orientations as the extremes in terms of the difference between Horizontal DF (DF_H) values and Vertical DF (DF_V) values, it is possible to ascertain a percentage range within which the difference between the vertical and horizontal light levels would be expected to fall. This will provide an outline assumption as to the relationship between the DF_H value, which is typically used to establish the distribution of light throughout an internal space, and the DF_V value, representing the amount of light that might reach the eye of the occupant. Based on this Case Study room and these two orientations, the range of difference between

the DF_H and the DF_V values is approximately 15-270% as shown in Table 8.2. This highlights the wide range of variability between light received on a horizontal plane and the light that could be expected to reach the eye of a person within the room when in a seated position.

Table 8.2: DF_{V_NORTH} and DF_{V_SOUTH} values as a percentage of DF_H values based on position within Case Study room

		DF_{V_NORTH} (facing window)	DF_{V_SOUTH} (facing away from window)
Position within Case Study room	Distance from the window (mm)	% of DF_H value	% of DF_H value
A	1100	130	15
B	2800	190	23
C	4400	270	38
D	6900	200	85

Table 8.2 shows that when a person within this Case Study room faces the window at position A they would be receiving 30% more light at the eye than would be reaching the horizontal desk surface, whereas if they turned through 180° to face the teaching wall (south wall) they would only receive 15% of the light falling on the horizontal surface. As the distance from the window increases to approximately 4.5m, and the illuminance level on the horizontal desk surface decreases, if a person was facing away from the window wall they would still be receiving less than 40% of the horizontal surface light at their eye level. In comparison the illuminance at a person's eye level facing towards the window at this point in the room would be 270% that of the horizontal value. This emphasises that lighting measurements taken at the horizontal desk surface are insufficient on their own to quantify the light reaching the eye of a person within the room.

The remainder of this Chapter presents both Horizontal and Vertical Daylight Factor measurements to encompass the extremes of light likely to be present at the eye in any of the given situations.

8.2.2 Effect of orientation of gaze

As described above, measurements of Vertical DF values were taken in 4 orientations at each of the four positions within the room to replicate a range of directions a person might be facing. Based on the variation shown by the two orientations in comparison to the horizontal measurement described above, it was felt relevant to also establish the variation in light reaching the eye level of a person based on their assumed direction of gaze.

By plotting the DF_v values together for all four orientations on a radar graph it is possible to clearly see the effect orientation has on the illuminance level at the assumed eye height of the occupant. This is shown in Figure 8.13 in which the notional position of the person at each of the four locations is at the centre of each radar diagram and the points on the graph indicate the DF value for this orientation of gaze.

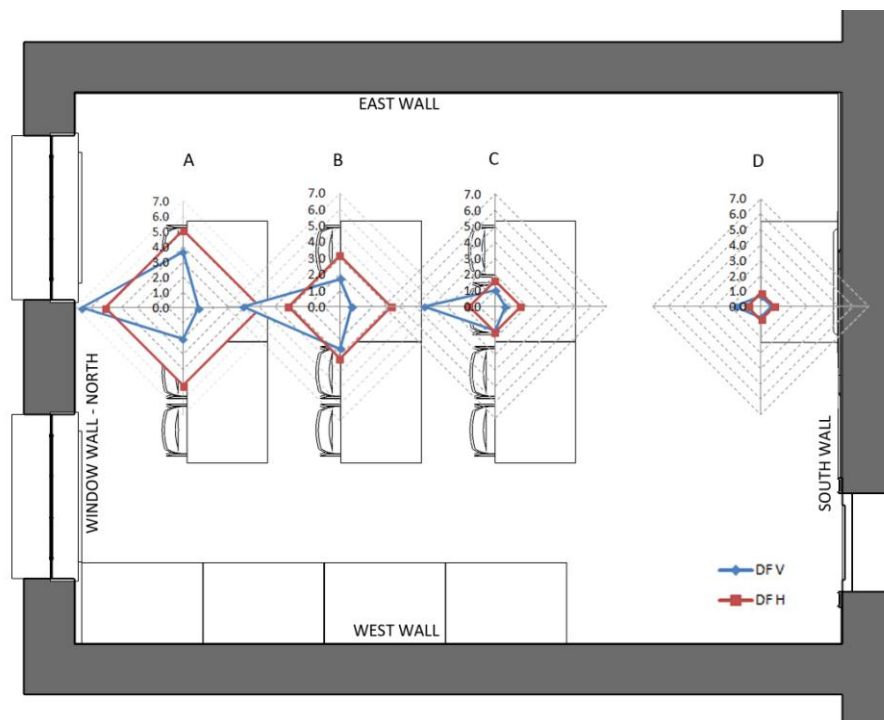


Figure 8.13: Plan showing horizontal and vertical DF values for the four orientations at each of the four locations within the room

It is clear from this radar graph in Figure 8.13 that the Horizontal Daylight Factor values are generally higher than the Vertical Daylight Factor values with the exception of the orientation facing the window. As highlighted above DF_v values are greatest when the vertical plane is facing towards the window in all four positions within the room. The difference between the DF_v values when facing the window and the other DF_v values varies depending on the position within the room and in particular the distance from the window. As the chosen points of

measurement were defined by seating positions within the room, based on a typical teaching configuration, they are not on the centre line within the room. As the window size and position is symmetrical around the centre line of the room, this offset of the measurement point will provide a better understanding of the effect of different locations within the room and in particular adjacency to the wall perpendicular to the window wall. This offset position within the room therefore has a different impact on the DF_V values facing 90° in either direction from the window wall, i.e. towards the east wall or west wall.

Table 8.3: DF_V values for East, West and South orientations as percentage of DF_V values for North orientation

	DF_{V_EAST}	DF_{V_WEST}	DF_{V_SOUTH}
Position within room	% of DF_{V_NORTH} value	% of DF_{V_NORTH} value	% of DF_{V_NORTH} value
A	55	30	10
B	30	45	10
C	25	35	15
D	40	40	45

The higher DF_V value measured facing East, compared to West, is due to the closer proximity to the east wall and the geometrical relationship with the brighter external sky in the West at this point, resulting in a greater amount of light being reflected back onto the light sensor. This can be seen in the rendering from the model of the room in Figure 8.14.



Figure 8.14: Rendering of Case Study room showing light pool from window onto East wall

At position B, the geometric relationship starts to favour the West facing gaze for DF_V , as the direct contribution of the external daylight from the West exceeds that reflected from the East wall. This shows that the amount of light possible to receive at the eye at any point will be

dependent on both location in the space and direction of gaze. The largest variations in DF_v light availability are found between facing directly at the window and all other directions, implying that it is these two relationships that need to be most carefully considered once a person is even a modest distance into a room.

For the Case Study, the difference between DF_{V_NORTH} and DF_{V_EAST} varies between 44-77%, while the difference between the DF_{V_NORTH} values and DF_{V_WEST} values is more consistent with a range of 57-70% across the depth of the room. As discussed above, the greatest difference is seen between the DF_{V_NORTH} and DF_{V_SOUTH} values where the difference is around 85% except for the furthest position within the room where it reduces to 57%. These variations at each measurement position are shown in Figure 8.15.

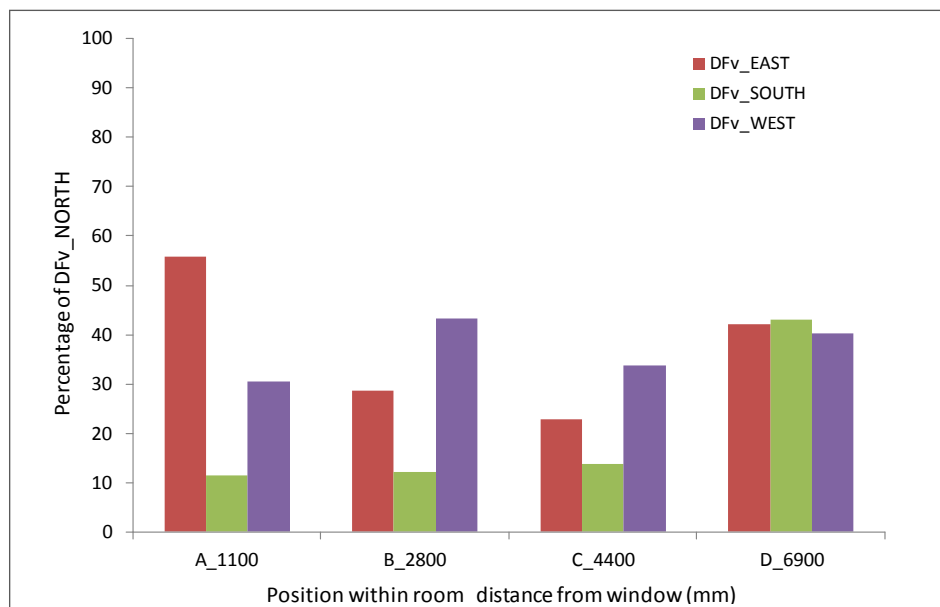


Figure 8.15: Bar chart showing the vertical daylight factor values for all 4 orientations at each of the measurement positions within the room, as a % of the North facing daylight factor.

Apart from the DF_{V_NORTH} values, in which a person would be facing the window wall, all other vertical daylight factor values are less than the Daylight Factor values measured on the horizontal plane. As expected, both Vertical and Horizontal Daylight Factor values reduce towards the back of the room, and at the farthest measured point from the window wall the DF_v and DF_h values are very similar; this is clearly shown in Figure 8.15. This point is approximately 6900mm from the window wall and suggests that the levels of natural light are too low at this point within the room to see a significant difference between illuminance levels at head height and those at horizontal desk height. Although a high window head height and

ceiling height will allow a greater penetration of light into the room there is a depth limit to the ability of a single aspect room to support good daylight distribution (BS 8206-2:2008).

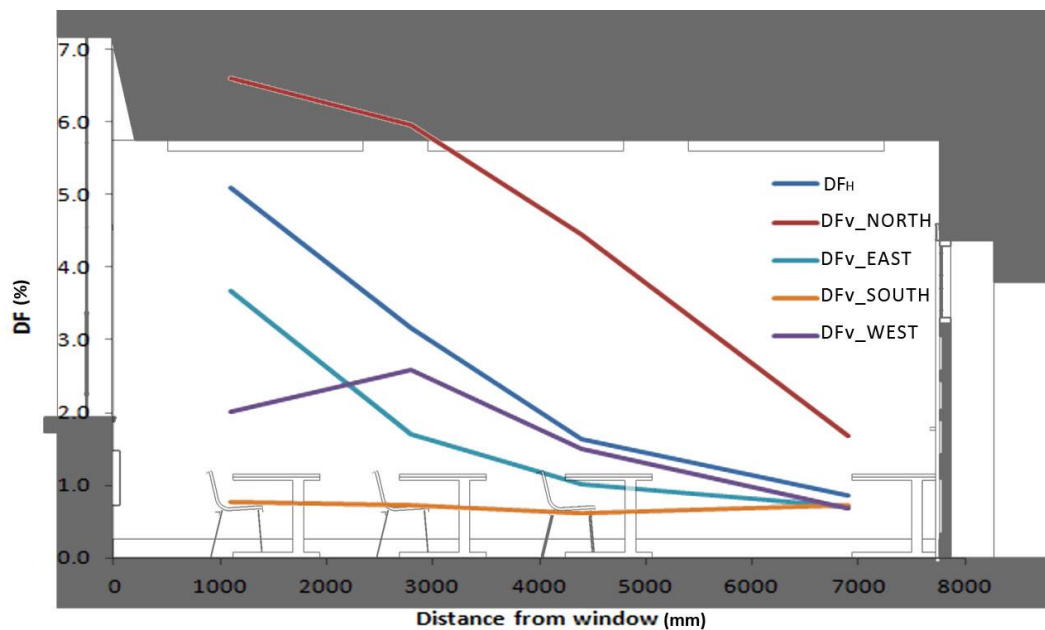


Figure 8.16: Graphical representation showing a comparison of DF_V values from 4 different orientations values across depth of room as well as DF_H values

The relationship between the Horizontal DF values and the Vertical DF values at the other points within the room vary depending on the orientation of the vertical plane. With the exception of position A the DF_{V_WEST} values are most similar to the DF_H values. The higher DF_{V_WEST} values are considered to be due to geometry reasons allowing additional light coming from the brighter part of the sky vault in this geographical location. The lower DF_{V_WEST} reading in position A is to do with the central window pillar blocking out this direct light contribution.

Figure 8.16 highlights that the orientation of a person within a given space in relation to the window wall does have a significant effect on the amount of light they could anticipate to receive at their eye level. Table 8.4 outlines the difference between the DF_V values and the Horizontal DF values at each seating position based on the orientation or the direction a person might be facing.

Table 8.4: DF_V values as a percentage of DF_H values based on orientation

Orientation at each position	% of DF_H value				Avg. % of DF_H value
	A (1100mm)	B (2800mm)	C (4400mm)	D (6900mm)	
DF_{V_NORTH}	130	190	270	200	198
DF_{V_SOUTH}	15	23	54	82	44
DF_{V_EAST}	72	54	63	83	68
DF_{V_WEST}	39	82	93	80	74

The results from this Case Study room show that the difference between the four orientations is not consistent across the depth of the room due to the central window pillar. Table 8.5 outlines the variation between DF_V values and DF_H values for each orientation based on depth within the room or distance from the window wall. The further into the room the smaller the variation between the DF_H and DF_V values as might be expected due to the limit of daylight penetration into the room. However it is clear that the variation in DF_V value across the room is more dependent on orientation at a point within the room than on distance away from the window in this single aspect room.

Table 8.5: DF_V values as a percentage of DF_H values based on distance from window wall

	DF_{V_NORTH}	DF_{V_SOUTH}	DF_{V_EAST}	DF_{V_WEST}	Avg. % of DF_H value
Distance from window	% of DF_H value	% of DF_H value	% of DF_H value	% of DF_H value	
1100	130	15	72	39	64
2800	190	23	54	82	87
4400	270	38	63	93	116
6900	200	85	83	80	112

In conclusion when considering the light availability at the eye, it is evident that it is important to know a person's position within a given space, not only from the point of view of the depth of the room as may have traditionally been considered but also in relation to the direction they are facing. It is evident that for a single aspect room the contrast between the different orientations of view will have a more significant effect than if there was daylight penetrating the space from two or more directions. This investigation has also shown that within this Case Study room the distance a person is from an adjacent wall can have an impact on the light they receive at eye level, depending on building geometry and the window aspect.

8.2.3 Effect of angle of gaze

Leading on from establishing how important the direction of gaze is in determining the amount of light that reaches the eye, the Case Study now goes on to consider the angle of gaze. In a large percentage of scenarios it would be difficult to predict the exact position of a person's head or specifically their angle of gaze throughout the day, whether they are looking straight ahead or down towards a horizontal plane in front of them. This work aims to understand the range of likely light levels to be achieved to establish the boundary parameters to the problem. For this Case Study, which is in a learning environment, the room layout is based on a traditional pedagogic model where the majority of people within the room will be facing towards the teaching wall. In this scenario it is also quite likely that the people inhabiting the room would spend a percentage of their time looking down towards the desk at a visual task, changing their angle of gaze.

From the work so far it has been shown that there is a significant difference between Horizontal and Vertical illuminance, which suggests that this 45° angle of gaze will also impact on the light that is received by their eyes, something that is also considered in research of education environments by others (Bellia, Pedace, & Barbato, 2013). To assess the impact of this change in angle of gaze, a series of light measurements were also taken at 45° from vertical, angled downwards towards the horizontal desk surface. This was graphically represented in Figure 8.7 and simulates the potential position of a person's head when looking down at a visual task on the desk. Calculating the DF values for a 45° inclined plane (DF_{45}) in the same four seated positions within the room through the four orientations enables a comparison to be made with the Vertical Daylight Factor and Horizontal Daylight Factor values. This will clarify the effect of the angle of the head/eye position on daylight received at eye level.

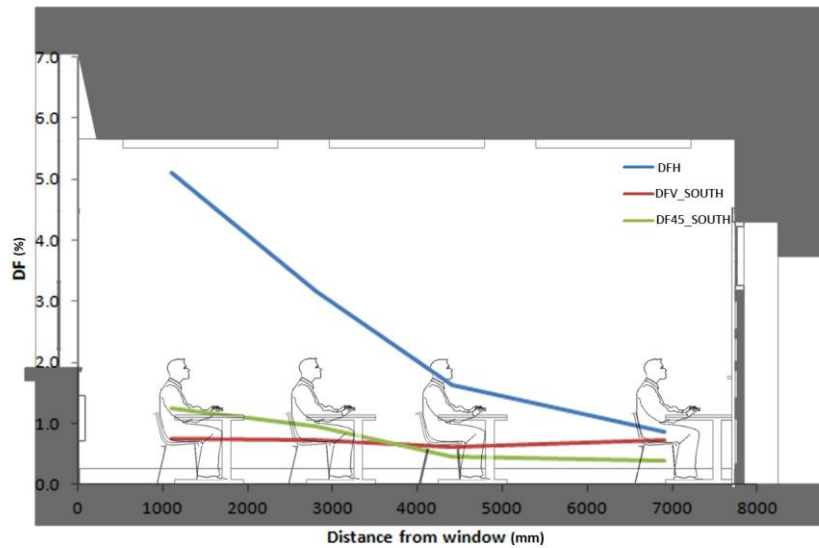


Figure 8.17: Section through room showing DF_V and DF_{45} values facing 180° from window wall in comparison to DF_H values

Figure 8.17 shows a comparison of the DF_{45} values with the DF_V and DF_H values assuming that the people within this Case Study room are facing the teaching wall (i.e. facing away from the window). It highlights that DF_{45} exhibits behaviour much closer to DF_V value than DF_H in this orientation. At the position nearest the window the daylight factor measurement at 45° (DF_{45}) is higher than the DF_V value although this is still a significant reduction from the horizontal DF values. It is considered that the 45° gaze position facing the desk is benefitting from a greater amount of light reaching the desk and being reflected back to the eye.

This apparently obvious relationship is emphasised by the fact that the further into the room the person is positioned the more the light falling on the horizontal plane decreases and in turn the DF_{45} decreases. At approximately 4m into the room from the window wall the DF_{45} value drops below the DF_V value and by the farthest point from the window the DF_{45} value is 50% lower than the DF_V . The 45° measurement helps clarify the point at which reflectance from the walls becomes a more important contributor to daylight levels than the direct light from the windows.

Table 8.6: DF_{V_SOUTH} and DF_{45_SOUTH} values as a percentage of DF_H values based on position within Case Study room

	DF_{V_SOUTH}	DF_{45_SOUTH}	DF_{V_NORTH}	DF_{45_NORTH}
Position within Case Study room	% of DF_H value	% of DF_H value	% of DF_H value	% of DF_H value
A	15	25	130	25
B	25	30	190	85
C	40	30	270	90
D	85	45	200	85

Table 8.6 shows the DF_V and DF_{45} values as a percentage of DF_H available at each position in the room when facing South towards the teaching wall as well as facing North towards the window. A person who is sitting in positions A to C (most likely student locations), either looking at the teaching wall or at the desk surface would expect to receive less than 40% of the light falling on the horizontal surface on average.

If the orientation facing away from the window wall is considered the worst case scenario, it is important to compare this with what might be considered the best case scenario, i.e. directly facing the window, or north as represented in this Case Study room. This table shows that the DF_{45} values facing North are more similar to the DF_H values, than the Vertical DF. This is with the exception of position A nearest the window, which is unrepresentative of a typical single aspect room for the reasons noted earlier in the Chapter. Plotting all the DF measurements on one figure, as shown in Figure 8.18, provides a clear picture of the relationship between the horizontal DF values and the DF_V and DF_{45} values.

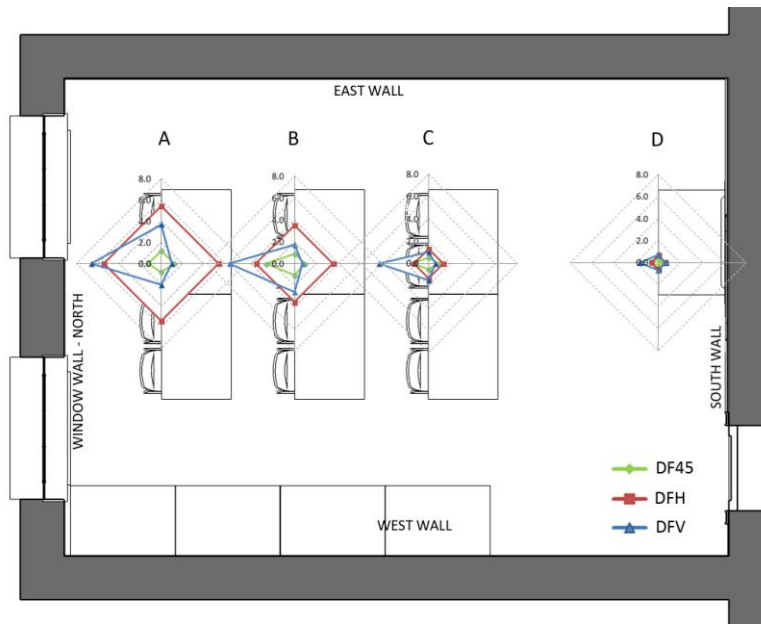


Figure 8.18: Plan showing horizontal, vertical and 45° tilted DF values for the 4 orientations at each of the four locations within the room

This analysis of the DF_{45} values across the Case Study room shows that the direction a person is facing or their orientation within the room does have an impact on the amount of light that is received at eye level. This is shown clearly in Figure 8.18. Overall the orientation or direction someone is facing within the room could alter the amount of light that reaches their eye level by 57% on average based on a downward angle of gaze. This further emphasises the potential inaccuracy of estimating the light reaching a person's eye level based solely on the horizontal illuminance measurement.

This analysis has also shown that the distance a person is sat from the window will have the greatest effect on the amount of light received at their eyes. Based on the results from this Case Study room there could be up to 68% variation in DF_{45} value across the depth of the room. This emphasises the observation made above that the majority of light received at this 45° downward facing angle is reflected from the horizontal surface therefore mostly influenced by the amount of direct light falling on the horizontal surface or reflected from other surfaces in the room.

Based on each position within the room which corresponds to a distance from the window wall the average DF_{45} value did not get above 1.4, overall a range of 16-85% less than the Horizontal DF values. This represents a considerable variation in light distribution between what is achieved at the horizontal plane to what might reach the eyes of a person sat looking toward the desk at a visual task. For example, if a point on a horizontal working plane achieves 500lux

the amount of light received at the eye of an individual person could range from 420lux down to 75lux depending on their position within the room.

8.2.4 Summary of daylight distribution studies

The work in this section of the thesis has been undertaken to assess the light levels reaching the eye of an occupant within the Case Study room. It has been shown that the light reaching the eye is significantly different to that reaching the horizontal desk surface, the traditional place for measurement of light levels, and therefore cannot be fully described using the horizontal DF alone. The concepts of vertical and 45° daylight factors were introduced and tested.

The Daylight Factor was chosen as a metric for this analysis as although it is a single point measurement it provides a clear picture as to the effect of the room design on a light received at a given point. Using the DF values makes it possible to compare a range of measurement positions as described in this chapter as well as the implications of the position and orientation of a person within the room has on the light received at the eye. Using the Daylight Factor metric also makes it possible to relate these measured DF values to the non-visual lighting needs of a building occupant proposed in Chapter 4 at a given time and geographical location by using external illuminance data. This approach is used in Chapter 9.

The findings from this investigation are that the orientation of a person within the room was shown to have the greatest impact on light reaching the eye based on the vertical Daylight Factor values. It was also shown that both the orientation and the distance from the window have a similar impact on the DF_{45} values. This also highlighted a stronger connection between the horizontal Daylight Factor values and the DF_{45} values, than between the horizontal DF values and vertical Daylight Factor values.

Overall, the implication of these findings is that utilising traditional Daylight Factor values measured on the horizontal plane alone may not be suitable for assessing whether non-visual, physiological needs are met by the lighting environment. For practical purposes, the DF_{45} measurement always recorded the lowest light level making it suitable for assessing the worst-case scenario and the DF_v values represented the average in terms of light distribution. As this thesis was not able to measure the length of time a person inhabiting this space would spend with their angle of gaze at vertical or 45° angle it is not possible to state which would be the most representative. For the purposes of this thesis, the DF_v values, which generally provide a compromise value between the horizontal and the DF_{45} values, have been considered the most

suitable parameter to use for an overall assessment of the light that could be anticipated to reach the eye level of a person in this scenario. This measurement value will be utilised throughout the rest of the thesis, though sensitivity tests will be undertaken using DF_H and DF_{45} to show the boundaries to the problem in some specific circumstances.

The use of the vertical daylight factor also makes it possible to assess the effect of the other aspects of the room that have an impact on the distribution of light, such as the colour of the walls and ceiling.

8.3 Virtual model

In order to find an effective way to establish the impact of changing a major building component, such as the glazing on the light that reaches the occupant, a virtual model of the room was created. It allows the testing of a range of parameter changes, including testing different glazing systems, something that would not be feasible in practice for this thesis. Other studies (Arsenault, Hebert, & Dubois, 2012) (Du & Sharples, 2012) have used scale models of a room to undertake similar research, but in order to see the effect of changing certain design parameters on the distribution of light within a space it was important to do this at full scale to avoid scaling effects. This method also aligns more closely with the process undertaken in the design development of buildings in practice, where virtual models are used to test design options at an early stage. This practice is set to accelerate with the growth in popularity of new tools such as BIM (Building Information Modelling) (Crotty, 2012) (Inyim, Rivera, & Zhu., 2015).

The physical testing undertaken in section 8.2 not only provided a comparative analysis of the horizontal and vertical light distribution throughout the space, but also a basis from which to ascertain the accuracy of the virtual model. Once this has been established, this then allows the virtual model to be confidently used to test the effects of changing physical components of the room, such as the glazing type, which are not feasible in practice. The modelling was undertaken using Autodesk *3ds Max Design 2009*, a piece of software typically used by designers to develop 3D visualizations of internal building environments.

8.3.1 Validation of 3ds Max Design lighting analysis tool

There are currently a number of different 3D modelling and lighting analysis software packages available for designers to utilise whilst developing new building designs. The most common lighting analysis engine is Radiance which is often included as a module within rendering software or environmental modelling software to provide a lighting analysis tool, such as within Ecotect or Daysim. 3ds Max Design 2009 was chosen as the modelling software to provide the virtual model of the Case Study room. As well as an ability to provide detailed lighting analysis the software is also able to model surface colour and texture accurately. In order for this virtual model to provide an accurate analysis of the impact of glazing specification on the internal lighting environment it is important that the software uses a validated approach.

Exposure™ technology, the lighting analysis module developed by Autodesk used within 3ds Max Design has been validated by a collaborative testing process undertaken by the National Research Council Canada, Harvard University and Autodesk (Reinhart & Breton, 2009). It utilises the Perez model similarly to Daysim 3.0 as well as a ray tracer application called mental ray®¹. Daysim 3.0 like other programmes has been using the Radiance backward ray tracer as well as a daylight coefficient which has provided the ‘gold standard’ in lighting analysis for many years. The evaluation concluded that *3ds Max Design* using *Exposure* technology provided comparable results for daylight indoor lighting environments to Daysim 3.0, therefore making it a reliable simulation tool.

Once the room is modelled it is possible to calculate potential light levels within the virtual space using the sky models programmed into the *3ds Max Design 2009* software. This information provides data relating to the distribution of light across the sky vault as described in Chapter 5. This piece of software has a number of options as to the assumed sky models which can be employed; to give daylight factor figures it is necessary to set the sky to ‘CIE Overcast Sky’. This will provide a uniform sky as the context for calculating the lighting values within the space, which will allow an analysis of the impact of the design of the space on the distribution of light as well as the impact of the specification of glazing on the light that reaches the room itself.

8.3.2 Calibrating the virtual model

For this virtual model to provide an accurate comparison of the effect of different glazing systems on light distribution within the Case Study room it was necessary for it to be calibrated using the physical measurements. This calibration would also establish what the key parameters causing any variation were. Computer models are often used within architectural practice to explore and develop the design of new buildings providing a three dimensional representation of the space. The accuracy of these models to represent the distribution of daylight is clearly an important factor in their successful use as a design tool.

The initial Case Study room model had accurately defined key attributes such as room shape and area, size and position of windows as well as the overall orientation of the room. These factors are understood to affect the amount and distribution of light within a space (Rennie & Parand, 1998) (CIBSE, 2012) and are some of the design parameters that are initially tested within a three dimensional model. The Case Study room was accurately modelled in respect of

¹ mental ray® is a high quality rendering application developed by Mental Images designed to be integrated into third party software packages such as 3ds Max Design.

these parameters as well as the existing glazing system; the light levels within this initial virtual model were then compared with the physical measurements taken in the room.

In the first stages of design development the finish of the surfaces within a space are not normally defined in detail and may be left as a neutral colour within a computer model. This provides the designer with an initial perception of the how the space will appear in three dimensions before more detailed design decisions are made. At this stage the surfaces within the computer model were specified as white. The DF values for both the horizontal working surface (desk top) - DF_H - and the vertical surface (DF_V) facing the south wall (180° from the window, towards the teaching wall) were compared with those taken from the physical measurements, as shown in Figure 8.19.

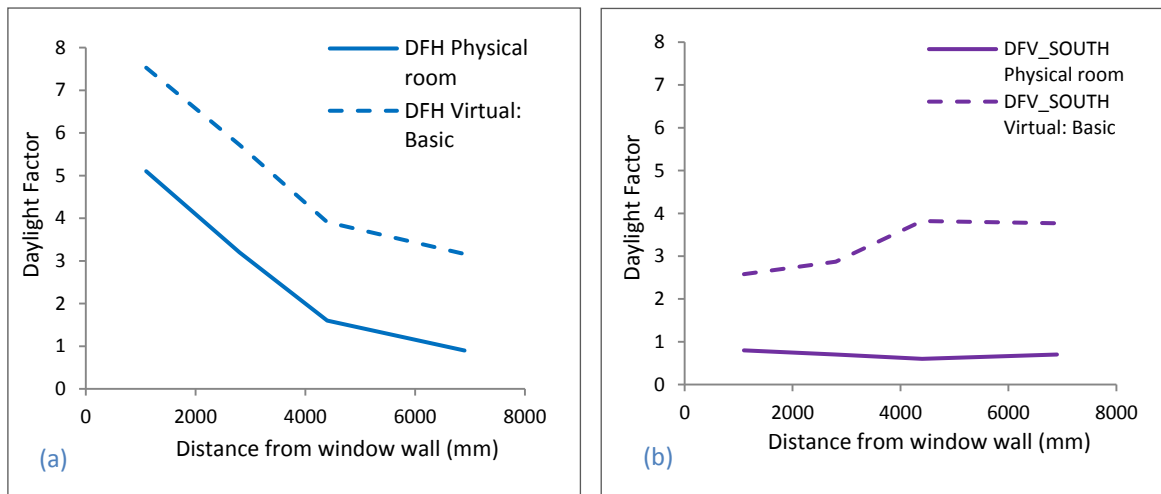


Figure 8.19: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the virtual model based on a set of basic parameters

It is evident that there is a significant difference between the two sets of DF values. The DF_H values show a similar form; both falling off across the depth of the room. The virtual model over estimates the DF_H values ranging from a 50 to 250% increase across the depth of the room. With the DF_V values in Figure 8.19(b) the relationship between the two data sets is different. The DF_V values from the virtual model increase moving further away from the window wall. The virtual model is also over-estimating the light that reaches the vertical plane towards the back of the room. This is considered to be due to the model over-estimating the light being reflected from the surfaces within the room, in particular the walls. The following sections look at the amendments made to the model to align the results more closely to the physical measurements.

8.3.2.1 Altering the reflectance of the surfaces

The reflectance values of the surfaces within a space have a significant impact on the light distribution. The initial reflectance values of the surfaces within this model are high, each surface given a reflectance value of 0.85, which was considered part of the cause of the over-estimated DF values seen in Figure 8.19. A percentage of the light that reaches any point within the room will be from inter-reflections (CIBSE, 2012). The properties of different materials specified within a space like this Case Study room will affect the reflectance values therefore affecting the light distribution. Assumed reflectance values for various types of surfaces are provided as a guide for designers within the British Standard Code of practice for daylighting (2008). These values for the Case Study room are shown in the third column in Table 8.7 and would reflect the data designers would use if going to this level of detail within a model. This data takes into consideration an assumed level of texture or roughness of each of the surfaces as this can have an effect on how the light is reflected and refracted.

Table 8.7: Reflectance values of key surfaces within Case Study room

Room surface	Finish	Assumed typical reflectance values	Measured Reflectance values
Wall	Light Green gloss paint	0.55	0.35
Floor	Dark Maroon/Brown carpet	0.1	0.02
Ceiling	White plasterboard ceiling tiles	0.86 ²	0.75
Desk surface	Medium wood veneer	0.2	0.1

The measured reflectance values shown in the fourth column in Table 8.7 were taken using a Konica Minolta LS-100 Luminance meter in accordance with its instructions. Although the assumed reflectance values from BS 8206-2:2008 (British Standards Institute, 2008) provide a better basis for the model than the initial white surface reflectance values used, there is a clear difference between the two sets of values. In particular the carpet and the walls were shown to be quite different to the assumed values. These measured reflectance values were assigned to the model whilst maintaining the initial 'neutral' white colour. Figure 8.20 below shows the effect on both the DF_H and DF_V values based on the assumed reflectance as well as measured reflectance values for the various surfaces, in comparison to the physical measurements as well as the initial computer model.

² Assumed value for standard specification lay-in ceiling tile taken from manufacturer's website <http://www.armstrong.co.uk/assets/global/commclgeu/files/Datasheet/2981.PDF>

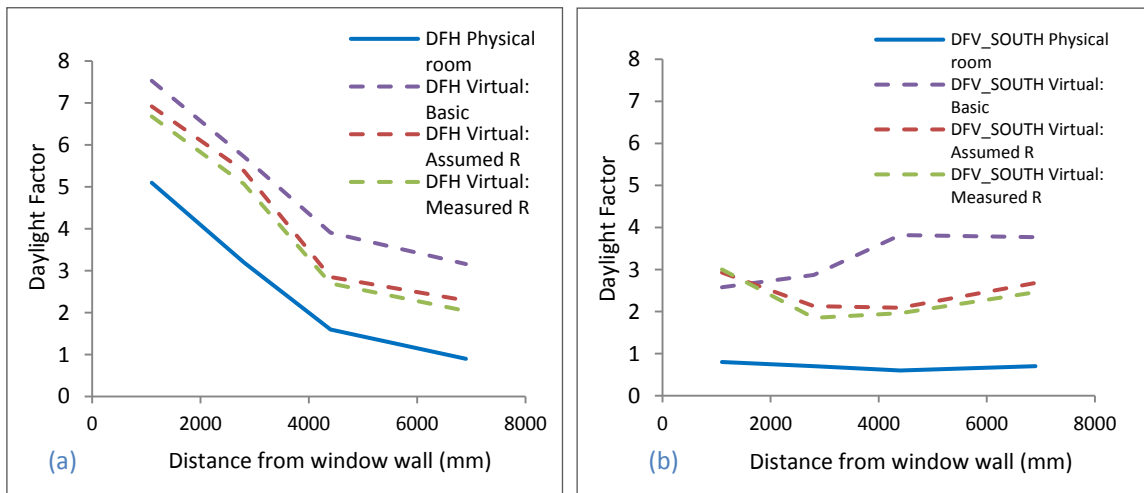


Figure 8.20: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the virtual model based on accurate reflectance values for the surfaces in the room

The DF_H values reported by the model are now nearer that of the physical measurements but there is a more significant change to the DF_V values. The daylight distribution is more in line with the physical measurements although still overestimating at some points. This emphasises the fact that using more realistic reflectance values within the model provides a better representation of the distribution of light across the room.

Although it was anticipated that there would be a difference to achieved light level readings based on the *Assumed* and *Measured* reflectance values, there is only a small although measurable effect on the DF_V values reported. In terms of the DF_H values in Figure 8.20 (a) there is an average variation of 6% from the assumed reflectance values to the measured reflectance values. There is a similar effect on the DF_V values showing an average 6% variation across the room. The maximum difference between the two sets of DF_V values is shown at point D furthest from the window.

Even though using accurate reflectance values improves the similarity between light distribution from the computer model and the physical room, a difference between the two was still evident. The final step of this calibration was to look at the colour of the surfaces. The colour of an object will affect how it interacts with light, the extent to which it reflects or absorbs light from certain parts of the visible spectrum. Although in reality the reflectance value measured in the physical room will take account of the colour of surfaces, with the *3ds Max Design* software it is possible to set the reflectance values of the surfaces within the model independently of the colour of that surface. It is acknowledged that this is not realistic as these two parameters are interconnected in the physical environment, but it does provide

an opportunity to assess the impact of each variable separately, the process which has been adopted in this calibration.

In this final step the colours assigned to each surface within the virtual model were initially matched by eye from a photographic record of the room. The impact of this initial adjustment to the colour of the surfaces, using these estimated colours, is seen in Figure 8.21 compared to the readings based on the measured reflectance values, as well as those taken from the physical room.

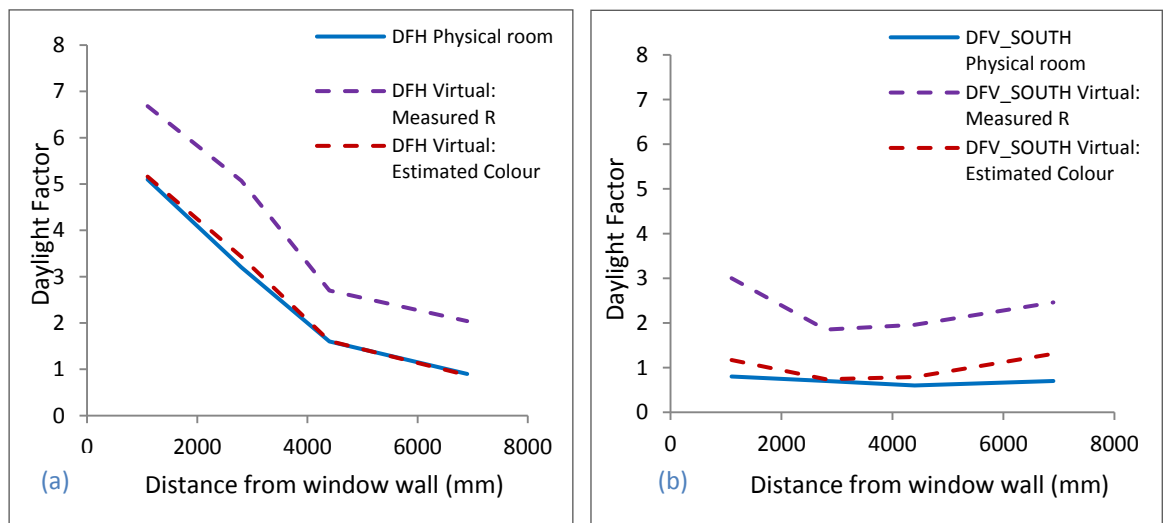


Figure 8.21: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the virtual model based on assumed surface colour specification as well as reflectance values

Making this initial adjustment to the colour of the surfaces within the virtual model has a significant effect on both DF_H and DF_V values. As shown in Figure 8.21 (a) using the estimated colour brings the DF_H very close to the physical measurements taken within the Case Study room. Although there is not the same accuracy with the DF_V values shown in Figure 8.21 (b) there is an increased similarity between the *Estimated Colour* and the *Physical room*. Unlike with the horizontal measurements, the virtual model is overestimating the vertical illuminance levels at the positions nearest and furthest away from the window; there is a difference between the measurements of 50% and 90% respectively. At position D the light meter is directly facing the south wall of the Case Study room, the increased DF_V suggests that the computer model is overestimating the amount of light reflected from this surface.

As this information relating to the colour of the surfaces was assumed based on photographic record from the room there is potential that these values may not be entirely accurate, possibly influenced by the exposure setting of the camera used. To improve the accuracy of

the model the colour of the surfaces within the room were given 'measured' values matched using a colour chart. This was accurately translated into the computer model using RGB values of the specific colour. The light levels within the room were then recalculated to ascertain whether there was any impact, the result is shown in Figure 8.22.

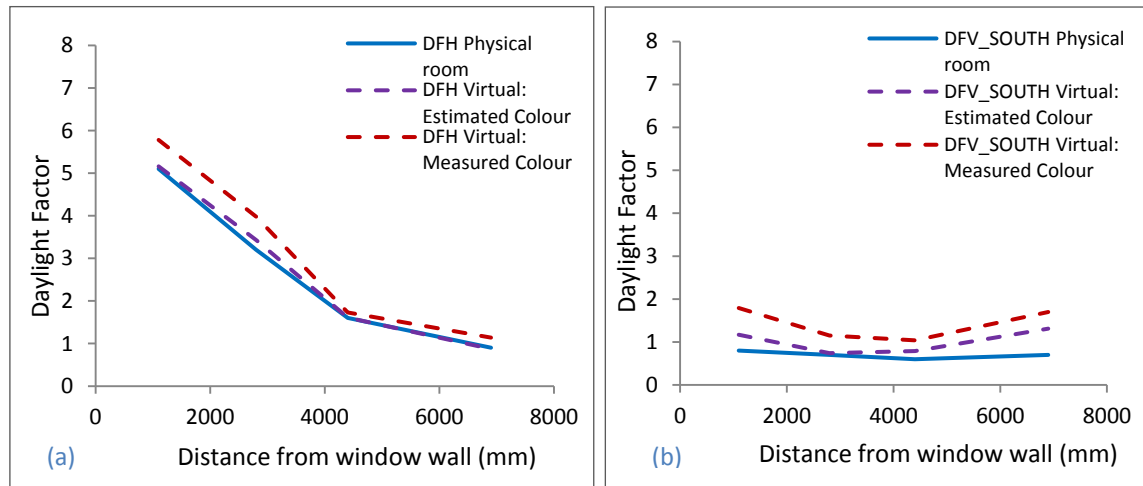


Figure 8.22: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the virtual model based on measured surface colour specification as well as reflectance values

Altering the colour of the surfaces in the room had an unexpected effect on the two sets of Daylight Factor values. The *Measured Colour* data presented an increased difference between this set of DF values and those from the physical measurements. This highlights the fact that the small adjustment of the tone or hue of a specified colour does have a measurable impact on the reflectance and absorptance of light within a space. The computer model is overestimating the DF_v values at either end of the room with the values at position D shown in Figure 8.22 (b) 200% of those measured from the physical room. It should be noted here that although this appears to be a significant variation the DF values at this position within the room are low with the physical measurement not exceeding a DF value of 1. An increase of 100% from this value still represents a low DF value.

It might be expected that position D, which is in close proximity to the south wall, would benefit from a greater amount of light being reflected from the surface of the wall in comparison to position C, 2500mm further into the centre of the room. However as the light level would be anticipated to be low at this distance from the window an increase in light level such as presented in Figure 8.22 (b) was not expected. This suggests that the computer model is still over-estimating the reflected light from this surface. The cause of this increase could relate to the brightness of the wall surface or an incorrect translation of the colour match from the room into the *3ds Max Design* software. To assess whether the computer model is

overestimating in respect of the other vertical surfaces within the room the light distribution was analysed based on two other orientations within the room. This comparison of *Estimated* and *Measured Colour* values with the Physical room measurements are shown in Figure 8.23.

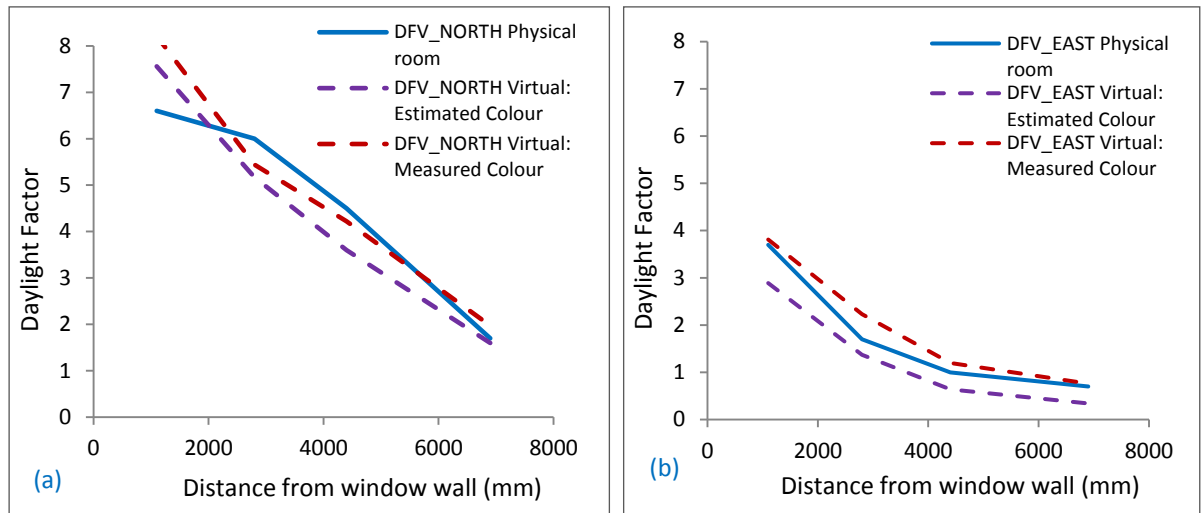


Figure 8.23: Comparison of (a) vertical_North and (b) vertical_East DF values taken in the physical room against those taken in the virtual model based on assumed and measured surface colour specification

Looking at the data for two of the other vertical orientations within the room, Vertical_North and Vertical_East shows that there is a different relationship between the *Measured Colour* readings and the physical room measurements. In the Vertical East readings shown in Figure 8.23 (b) the *Measured Colour* shows a greater similarity to the physical measurements than in Vertical North or Vertical South. For this orientation the *Estimated Colour* readings underestimate the physical measurements. The relationship between the *Estimated Colour* readings and the *Measured Colour* readings is similar across all the orientations shown above with an average variation of 20-40% across the depth of the room. These results suggest that both methods for calibrating the surface colours within a space provide similar validity in terms of the accuracy against the physical measurements.

Further iterative amendments to the colour of the surfaces within the room were undertaken to assess whether a closer alignment to the physical measurements could be achieved. A full description of the findings of these amendments can be found in Appendix F. The final outcome showed a further improvement in the agreement of the virtual and physical measurement, although the final version still over-estimated the Horizontal daylight distribution by an average of 20% across the depth of the room. A graphical representation of this is shown in Figure 8.24.

Taking all the vertical orientations into account the final computer model over-estimates the daylight distribution between 5-150% across the depth of the room. This over-estimation is seen most significantly with the South orientation which presents a variation to the physical measurements of 45-150% across the depth of the room. Excluding the readings for this South orientation the average variation is 5%.

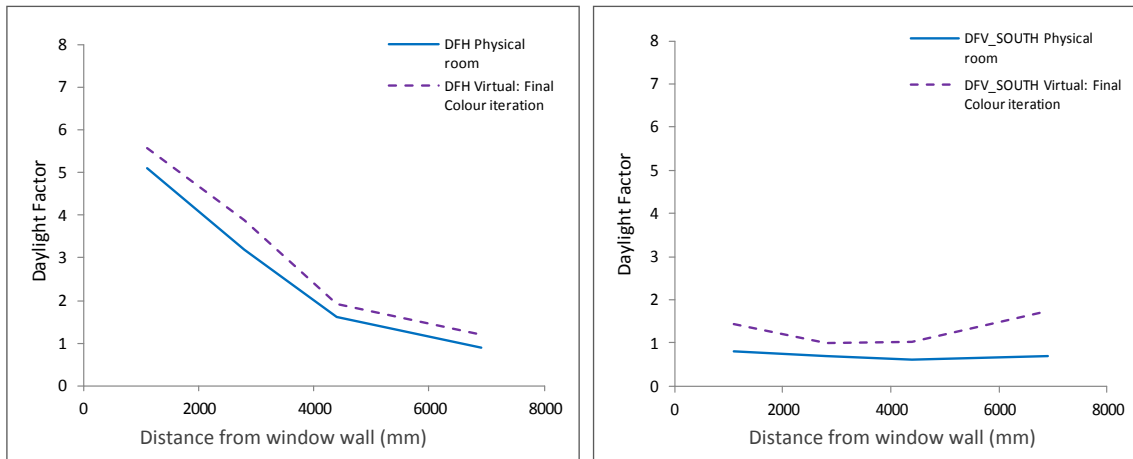


Figure 8.24: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the final iteration of the virtual model

8.3.3 Summary of the calibration of the virtual model

The examination of the parameters that influence the accuracy of the computer simulation of the Case Study room has demonstrated that there are a number of attributes specific to the design and material specification of a space that will have an impact on the distribution of daylight. Table 8.8 summarizes the impact of the key parameters described above on light distribution. The change is described in terms of the percentage variation in Daylight Factor from the initial ‘basic’ computer model (which described the space with a neutral colour and high reflectance values on all surfaces) to the version of the model using accurate reflectance and colour values.

Table 8.8: Average variation of DF values based on significant adjustment of surface finishes

	Average variation based on adjustment to a specific parameter	
	Accurate reflectance values	Accurate colour information
DF Horizontal	20%	45%
DF Vertical_SOUTH	25%	55%
DF Vertical (all orientations)	20%	45%

The variations described in Table 8.8 suggest that accurate colour information is more significant than reflectance values on the distribution of light within an internal space.

Comparing the variation between DF values based on more incremental changes to the information included in the model, it is possible to ascertain the impact smaller adjustments may have. For example adjustment to the reflectance value has a small but measurable effect on the distribution of daylight but similar adjustments to the tone or brightness of surface colours can still have a considerable effect as shown in Table 8.9.

Table 8.9: Average variation of DF values based on small adjustment of surface finishes

	Average variation based on adjustment to a specific parameter	
	Assumed to accurate reflectance values	Estimated to Accurate colour information
DF Horizontal	5%	15%
DF Vertical_SOUTH	5%	30%
DF Vertical (all orientations)	5%	35%

These tables also highlight that altering these parameters can have a greater impact on the vertical daylight distribution than the horizontal, this is evident with the adjustment to colour shown in Table 8.9. This is significant when considering the importance of light received at eye level of a person within an internal space. It would suggest that more care is needed when assessing the daylight distribution on vertical surfaces throughout a space based on a computer simulation.

This process has shown that if the colour and reflectance data used to model internal spaces is not accurate it is possible that the projected illuminance levels that would be anticipated within an internal space could deviate significantly - up to 55% from the actual values achieved in the example of the Case Study room. If no colour or reflectance values are used at all from the basic 'white' model, then the predicted illuminance value vary even more dramatically - by up to 250% from the measured value, depending on the position within the room, within the Case Study room.

The main conclusion is that, if lighting environments are going to be simulated by computer in order to evaluate the potential success of a space to support both the visual and the non-visual systems, then there is a clear need for an accurate representation of the space, including surface finishes.

8.4 Effect of changing the colour of surfaces within model

Having calibrated the model we are now able to look at the impact of changing elements within the model, such as colour. As already shown, just adjusting the colour of a surface by small increments noticeably altered the light distribution and availability at the eye within the space. Making more fundamental changes to the colour of the walls in the Case Study model would therefore be anticipated to have a significant effect on the light distribution throughout the space. To test this, a range of different colours were assigned to the wall surfaces and the light readings across the room recalculated. The comparison of these readings is shown in Figure 8.25.

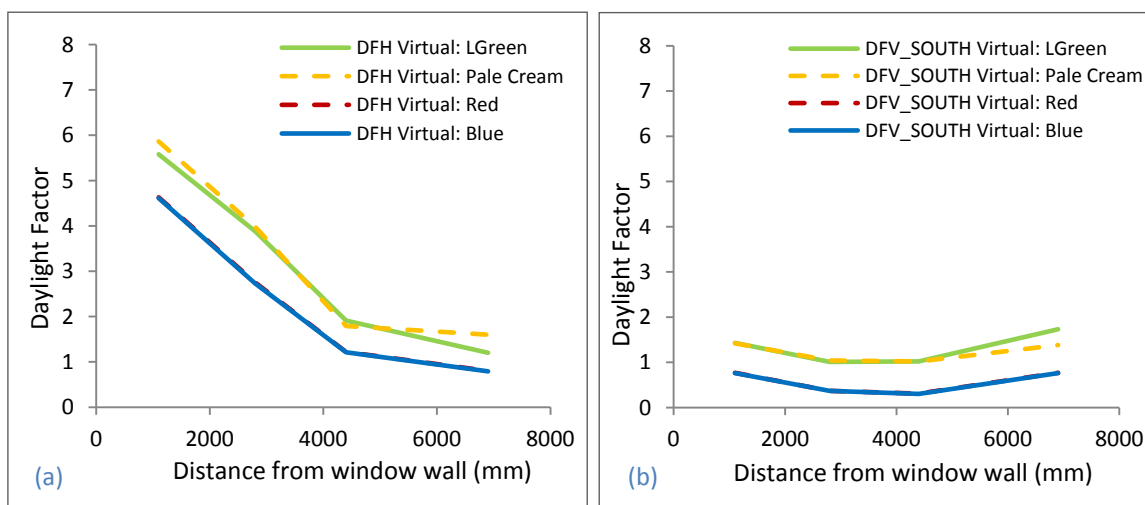


Figure 8.25: Comparison of (a) horizontal and (b) vertical DF values based on different wall colours

The data presented in Figure 8.25 shows that changing the colour of the walls within a space does indeed have a significant impact on the distribution of light. As discussed above, the colour of a surface will affect the amount of light it reflects and absorbs therefore altering the amount of light that is ultimately distributed around the space.

Figure 8.25 shows that both the red and blue walls have more of a significant effect on the DF values across the depth of the space than the pale cream, and this is in agreement with expectation. For the Vertical Daylight Factor values these two colours present a variation of 45-70% in comparison to the original Light Green wall colour. For the Horizontal Daylight Factor values these two colours present a variation of 15-35%. The pale cream wall colour provides a very similar light distribution to the Light Green wall colour across the space with the exception of the position furthest from the window. At this point in the room there is a deviation of 20% from the Light Green readings. The impact on the daylight distribution within

the Case Study room based on adjusting the colour of the walls from the original light green is shown in Table 8.10.

Table 8.10: Average variation to DF values based on adjusting wall colour from original Light Green

	Average variation from original wall colour		
	Pale Cream	Red	Blue
DF Horizontal	+10%	-30%	-30%
DF Vertical_SOUTH	-5%	-60%	-60%
DF Vertical (all orientations)	+15%	-40%	-40%

Table 8.10 highlights that changing the wall colour within a room can have a considerable impact on the light distribution throughout the space. This is again more noticeable for the Vertical Daylight Factor values than the Horizontal Daylight Factor values, and shows that changing the colour of wall surfaces within the room has a noticeable impact on the light that is received at the eyes of a person within this room. Based on research outlined in Chapter 4 this could in turn have an effect on their well being.

8.4.1 Summary of effects of changing elements within virtual model

These results highlight the need for care when using a computer generated model of a physical space for assessing the amount of light available at the eye. Over simplified representations of the surfaces within the room has a measurable effect on the accuracy and quantity of light distribution predicted by the model. Assigning the correct colour and reflectance to surfaces can have a significant impact on the light received at various points within the room. The model has also shown that changing the colour of wall surfaces affects the Vertical Daylight Factor values to a greater degree than the Horizontal Daylight Factor values. As discussed earlier this shows that wall colour has a significant impact on the light received at the eye of a person within the room.

When considering the design and construction of buildings it is quite common for the specification of finishes such as a chosen paint colour or paint manufacturer to be changed during the construction phase. This simple investigation shows that it could potentially make a significant difference to the light that is received. This observation is also relevant in terms of the refurbishment of existing spaces. It is often the case that once a building has been in use for 12-24 months it is likely that a percentage of the spaces will be refurbished which often includes the repainting of wall finishes.

8.5 Summary and conclusions to Chapter 8

This evaluation of light distribution within the Case Study room has shown that besides the physical dimensions, location and orientation of a room, the factors that affect the availability and quantity of daylight at the eye within a space are:

- The colour of the room's surface finishes
- The reflectance of the room's surface finishes
- The direction and angle of gaze of the occupant

These findings substantiate guidance on the daylight design of buildings (Rennie & Parand, 1998) (CIBSE, 2012) (British Standards Institute, 2008) such as the effect of depth of the room.

The evaluation of light distribution across both horizontal and vertical planes in the Case Study room highlights the difference between the amount of light that reaches the working surface and the amount that might be expected to reach the eyes of a person within the room. The measured Vertical DF values ranged between 15-270% of the Horizontal DF values based on all the measurement positions within the room. This wide range highlights the fact that to establish whether a given space will provide enough light to support the non-visual system it is not enough to rely on the horizontal illuminance measurements.

Based on the recommended horizontal illuminance level of 300lux for the teaching activity undertaken in the Case Study room (CIBSE, 2012) the variation in vertical illuminance shown in this Case Study room would mean that between 45-285lux would be anticipated at the eye level of someone sat at a desk, unless they were directly facing the window. Based on the research outlined in Chapter 4 this would suggest that a person continually sat within this room would not receive enough light to stimulate non-visual processes, such as circadian phase-setting, unless they were directly facing the window. This orientation towards the window would not be typical if this Case Study room were being used in the current classroom arrangement.

Taking into consideration all orientations within the Case Study room, the DF_v value varies by on average 53% in comparison to the horizontal DF value, based on the orientation of a person within this space or their direction of view. This therefore means that the function of the space and the activities that take place within it will have a significant impact on the light that

reaches the eyes of a person within that room. These factors should be considered when planning the layout of a space for a particular activity.

Using the *3ds Max Design* model of the Case Study room made it possible to establish that the specification of surface colour and materiality have a significant impact on the distribution of light. Again this substantiates existing guidance on lighting design and analysis of lighting environments (British Standards Institute, 2008) (CIBSE, 2012) but it also emphasises the implications of changing these aspects throughout the life of the building. For example, changing the colour of the wall surfaces within the room could reduce the amount of light reaching the eye of a person by up to 40% on average. Although this is something that designers may be aware of, they might not be aware of how much of an impact changing the colour of a wall has on the daylight availability at the eye.

As a side note, a number of studies have investigated the potential link between the colour of surfaces within buildings and peoples' mood and performance but the cause of any positive or negative effect has not been proven conclusively. For example, as part of a recent study by Barrett et al (2012) the colour of surfaces within the classroom environment were seen to have an impact on the performance of primary age children. This thesis would suggest that some of this performance impact might be explained by the effect that the colour has on the quantity of light reaching the eye, and therefore potential alertness.

In summary, this chapter has shown that surface colour and reflectance, along with the layout and use of a room, have been identified as having an important impact on the light that is received at the eyes of a person within a space, even before the effect of the choice of glazing system is considered. It has also shown that these things not only need to be considered at the initial design development phase but also in relation to the use of that space over the life of the building. This will in turn have an impact on whether a given space will provide enough light to support the human non-visual as well as the visual system, and therefore the well being of the people that use the space.

Chapter 9 will complete this analysis by considering how this room, with all its variations, might function with various external light levels and choices of glazing system.

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Chapter 9

Results: The impact of glazing specification on daylight received at the eye within the Case Study room

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9 Results: The impact of glazing specification on daylight received at the eye of the occupant

This chapter brings together all the elements previously evaluated in order to establish the impact of the choice of glazing specification on the light that a person within this Case Study room will receive at their eye. It will build on the evaluation of the design parameters in Chapter 8 by putting the Case Study room in geographical context. The weather data for Cardiff was obtained using the methodology described in Chapter 5.

This Chapter will look at the relationship between the geographical location and the chosen glazing system on the amount of light received at the eye of a person. It will include three locations within the northern hemisphere; Helsinki, Cardiff and Tangier as well as establishing the impact of the time of day on the available external illuminance in the context of the non-visual response to light. By evaluating these parameters within the context of the Case Study room it will also take into consideration the design parameters related to the room such as depth of room, colour and materiality of surfaces as well as the orientation of the person within the room as discussed in Chapter 8. This evaluation will provide an assessment of how the relationships between these parameters affect the ability of a given space or lighting environment to support the well-being of the occupant, based on non-visual requirements.

There are a number of different ways of representing the data as established in the previous chapters; this chapter will be using vertical Daylight Factor (DF_v) to define the vertical illuminance levels. It will also be using lower and upper illuminance thresholds for the stimulation of circadian phase-resetting and subjective alertness as non-visual processes, to establish the success of light stimuli on occupant well-being. The parameters for these were established in Chapter 4 and are redefined in Table 9.1.

9.1 Lighting parameters for occupant well being

As outlined in Chapter 4 there are specific lighting parameters that are important to human well-being which need to be considered separately from the visual system. Research into the connection between light received at the eye and non-visual mechanisms within the human body has established that there are a number of factors which influence the response. As discussed in Chapter 4 there are four main parameters; spectral quality, quantity, timing and duration.

Research in particular suggests that the required illuminance thresholds vary depending on the specific non-visual response, whether this is entrainment of the sleep/wake cycle or regulation of hormone release. As this thesis is looking to establish whether the design and specification of glazing systems has an impact on the health and well-being of the building occupant, the quality and quantity of daylight received is the focus. Acknowledging the significance of the timing of light stimulus, as mentioned previously, this thesis will focus on two non-visual responses that can be connected to light received during the day time; circadian phase-shifting or entrainment stimulated with early morning light exposure, and subjective alertness stimulated by light received during the afternoon.

As the internationally accepted system of photometry is based on the photopic or human visual response, it does not include considerations for non-visual responses to light. As outlined in Chapter 4, by using a mathematical process developed by Bellia et al (2011), based on a proposed action spectrum for circadian response, it is possible to define a threshold illuminance range as set out in Table 9.1. This table also includes other key parameters proposed to satisfy these two non-visual processes as discussed in Chapter 4. As the scientific research is incomplete, universally accepted lighting parameters for the non-visual system have not been agreed, therefore this thesis will use the assumed parameters set out in Table 9.1 to assess the success of the Case Study room to support the non-visual system.

Table 9.1: Proposed lighting parameters to support two non-visual processes

Non-visual response	Intensity		Timing	Duration (approx)
	Lower threshold	Upper threshold		
Circadian phase-resetting	370lux	800lux	Early subjective morning 06.00 – 10.00	2 hours
Subjective alertness	200lux	840lux	Subjective day 12.00 – 17.00	1-2 hr

9.1.1 Achieving the illuminance threshold

In terms of establishing whether a particular space will achieve the illuminance threshold levels to stimulate these non-visual responses to light, the proposed Daylight Factor (DF) values as set out in Chapter 8, provide a means by which it is possible to establish the external illuminance necessary to achieve a given illuminance level internally. For example, if the DF value was 1 at a given point within the room, to achieve the lower threshold for circadian phase-resetting of 370lux there would need to be an external illuminance level of 37,000lux. Whereas if the upper illuminance threshold of 800lux for circadian phase-resetting was required with this DF value of 1 an external illuminance of 80,000lux would be needed. As the DF values increase the lower the external illuminance necessary to achieve a required internal illuminance level.

By taking the proposed illuminance thresholds for each non-visual response to light it is possible to establish a simple breakdown of the external illuminance levels necessary based on a range of DF values potentially achieved within an internal space. This is shown in Table 9.2.

Table 9.2: External illuminance necessary to achieve threshold values dependent on a specific daylight factor at the eye

Non-visual response: Circadian phase-resetting			Non-visual response: Subjective alertness	
DF value	External illuminance to achieve lower threshold @ 370lux	External illuminance to achieve upper threshold @ 800lux	External illuminance to achieve lower threshold @ 200lux	External illuminance to achieve upper threshold @ 840lux
0.3	123,000	270,000	67,700	280,000
0.6	61,700	133,000	33,300	140,000
1.0	37,000	80,000	20,000	84,000
2.0	18,500	40,000	10,000	42,000
3.0	12,300	27,000	6,700	28,000
5.0	7,400	16,000	4,000	16,800
6.0	6,150	13,500	3,500	14,000
6.6	5,600	12,100	3,000	12,700

Table 9.2 highlights that when the DF values drop below 1 the external illuminance levels necessary to achieve the upper thresholds are unrealistic to achieve. To emphasise where this would be the case these values have been greyed out within the table.

The values shown in Table 9.2 are also represented within a graph in Figure 9.1 which highlights that when the Daylight Factor value drops below 2% there is a significant increase in the necessary external illuminance value to achieve both lower and upper illuminance thresholds. In comparison if the Daylight Factor values achieved within an internal space are

≥5%, typically recommended for spaces that are to rely on daylight (BS 8206-2:2008, 2008), external light levels would not need to exceed 17,000lux in order to achieve the lower and upper threshold values for both non-visual responses.

Current lighting guidance (BS 8206-2:2008, 2008) (CIBSE, 2012) recommends that in order for a room to appear daylight an average Daylight Factor of at least 2% would need to be achieved and an average DF value ≥5% would mean that no supplementary electric would be needed. Considering the threshold ranges for non-visual response stated in Table 9.1 it might suggest that this guidance on daylight factor values would be sufficient to achieve the necessary illuminance at the eye. However, as was shown in Chapter 8 there was a significant difference between horizontal and vertical illuminance levels with the Case Study room, the DF_v values ranging between 15-270% of the horizontal DF values. This highlights the fact that it is not possible to rely on horizontal illuminance measurements alone to establish whether the lighting environment within a room provides enough light at the eye of the occupant. For this reason vertical Daylight Factor (DF_v) values are going to be used throughout the rest of this thesis as discussed in Chapter 8.

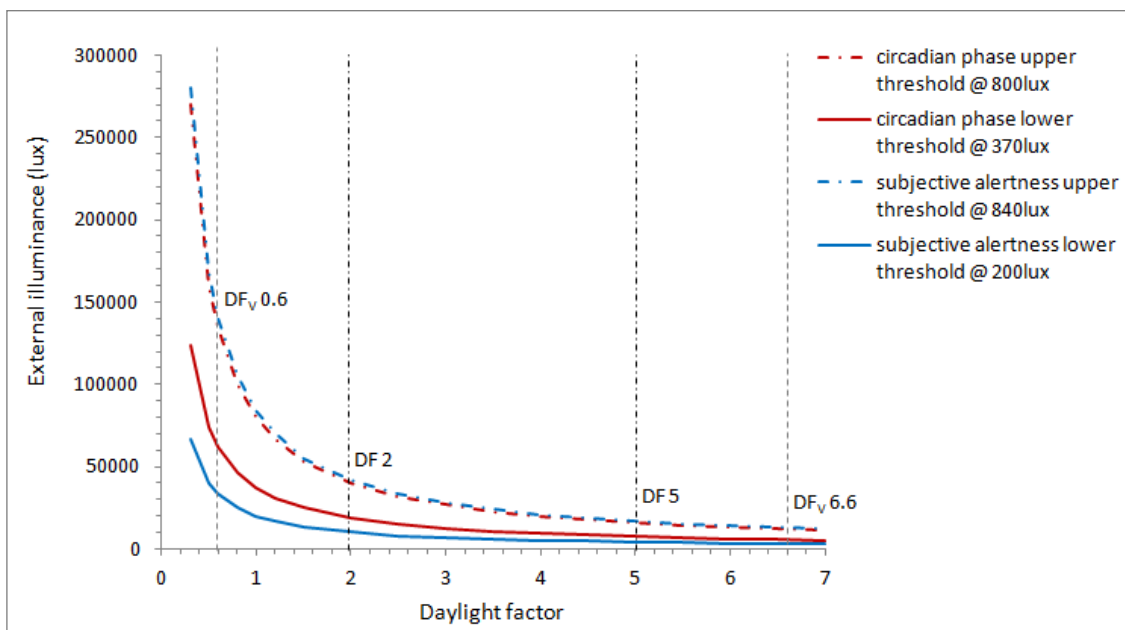


Figure 9.1: External illuminance necessary to achieve the lower and upper thresholds values to stimulate non-visual responses based on daylight factor values

As outlined in Chapter 8, the DF_v values within the Case Study room were in general significantly lower than the horizontal DF values; the minimum to maximum range for DF_v was 0.6-6.6. In order to achieve the lower illuminance threshold for circadian phase-resetting of 370lux, based on the range of DF_v values measured in the Case Study room, there would need

to be an external illuminance of between 5,600 - 61,700lux. If it were necessary to achieve the proposed upper illuminance threshold of 800lux at the eye the external illuminance level would need to reach between 12,100-133,300lux as can be seen in Figure 9.1. As acknowledged in Table 9.2 no location within the Northern hemisphere would achieve the uppermost figure of 133,300lux therefore this DF_V value of 0.6 would never achieve the upper illuminance threshold for circadian phase-resetting.

If it were assumed that this Case Study room were being used in a traditional teaching arrangement the majority of the people within the room would be facing away from the window. Based on this arrangement it would be feasible to remove the DF_{V_NORTH} values (facing the window wall) achieved within the Case Study room from the range. By removing these values the range of DF_V values achieved reduces to 0.6-3.7, which in turn increases the external illuminance levels required to reach the lower illuminance threshold for circadian phase-resetting to between 10,000-61,700lux. To achieve the proposed upper illuminance threshold for both non-visual responses the external illuminance would have to increase to between 22,700-140,000lux. A proportion of the upper end of this range of external illuminance would not be achieved as discussed earlier. Furthermore, when the DF_V value drops below 3, the external illuminance needed to achieve the proposed upper threshold illuminance for both circadian phase-resetting and the stimulation of subjective alertness, will become less likely to achieve for any significant amount of the year in most northern hemisphere locations.

It is important to note that the DF_{45} values achieved within the Case Study room were lower than the DF_V values by 45% on average. This significantly reduced DF value means the external illuminance has to be higher again in order to achieve even the lower threshold values for non-visual response. Based on the DF_{45} values within the Case Study room it would be unlikely that many locations within the northern hemisphere would achieve the external illuminance necessary to achieve the upper illuminance threshold at the eye for either non-visual response.

As the external illuminance level at a given location is a key factor in whether the required amount of light reaches the building occupant it is necessary to note that this thesis will use the diffuse component of the external horizontal illuminance as the measure of available daylight. This value will be considerably lower than the global horizontal illuminance value. As described in Chapter 6, solar control can often be one of the main priorities in terms of glazing specification in order to control internal solar gain as well as limiting problems related to glare.

The siting and orientation of buildings as well as the design of facades will often take into consideration the sun path at the given location in order to limit the penetration of direct light into the building interior. This is especially the case in locations nearer to the equator where high levels of direct sunlight throughout the year cause overheating within buildings. Although it is acknowledged that global illuminance at a given location, combining both direct and diffuse components of daylight, will be much higher at periods throughout the year it is considered that using the diffuse horizontal illuminance measure alone is a much better indicator of useable daylight in buildings.

9.1.2 Effect of geographic location on external illuminance

As discussed in Chapter 7 the geographical location within which a building sits will have an impact on the amount of daylight that is available throughout the year. The most significant factor affecting available external diffuse illuminance is the latitude which in turn relates to the impact of the different seasons on available external illuminance. This variation in external diffuse illuminance levels depending on latitude will also be noticeable across each day.

The specification of certain building components, such as the choice of glazing system, should be chosen with reference to the amount of light that is available externally. This thesis will use external diffuse illuminance data for three Northern hemisphere locations to ascertain the impact of geographic location and more specifically latitude; Helsinki, Finland, Cardiff, UK (location of the Case Study room) and Tangier, Morocco. This will then be used to assess the impact this availability of daylight in combination with a chosen glazing system has on the provision of internal illuminance levels to support the non-visual requirements outlined above.

As daylight is not a constant light source, the external diffuse illuminance level is continuously changing throughout the day and throughout the year, it is therefore often more informative to state a percentage of the year that a particular illuminance level is achieved (CIBSE, 1999). This type of illuminance data is often filtered by the hours within a typical working day, for example 9am to 5pm. This provides information about the availability of daylight during the period of time in which the majority of people are at work, a large percentage within office environments.

Using external diffuse illuminance data extrapolated from *SATEL-LIGHT* (SATELLIGHT, 1997) a recommended source of climate data (BS 8206-2:2008, 2008) the percentage of the year that a certain external diffuse illuminance level is likely to be exceeded at three locations was established. As this external diffuse illuminance data is provided as monthly mean of hourly

values it is also possible to filter it to establish the percentage of the year a certain illuminance level will be achieved during a particular period of the day.

The following section will compare the external daylight availability of these three locations in and the percentage of the year that external horizontal diffuse illuminance is exceeded during a standard working day. An overview of the potential internal illuminance levels which would be anticipated based on the DF_V values achieved within the Case Study room, in reference to the proposed illuminance thresholds for non-visual response, will also be presented.

9.1.2.1 External diffuse illuminance values for Cardiff

As stated in Chapter 8, the Case Study room was located in Cardiff, UK; this location has latitude of $51^{\circ}28'N$, similar to that of London and Bristol within the UK. The percentage of the year the given external horizontal diffuse illuminance is exceeded is presented in Figure 9.2 and Figure 9.3, based on climate data from *SATEL-LIGHT*.

As discussed above the Case Study room achieved a range of DF_V values between 0.6 and 6.6, from which it was possible to ascertain the required external diffuse illuminance in order to achieve the proposed illuminance thresholds for non-visual response, shown in Table 9.2 above. Figure 9.2 highlights the percentage of the year the proposed upper illuminance threshold of 800lux to stimulate circadian phase-resetting might be achieved based on these DF_V values, while Figure 9.3 shows this same data but for the proposed lower illuminance threshold of 370lux.

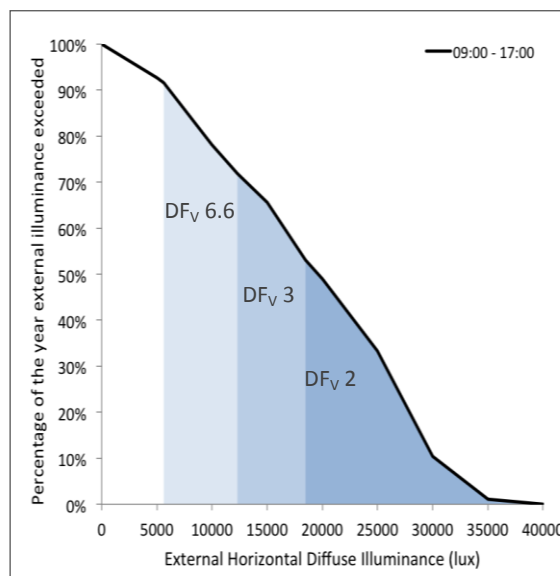


Figure 9.3: Annual external horizontal diffuse illuminance levels exceeded between 9am-5pm in Cardiff, UK and percentage of the year that the lower illuminance threshold of 370lux is exceeded based on a range of DF_V values

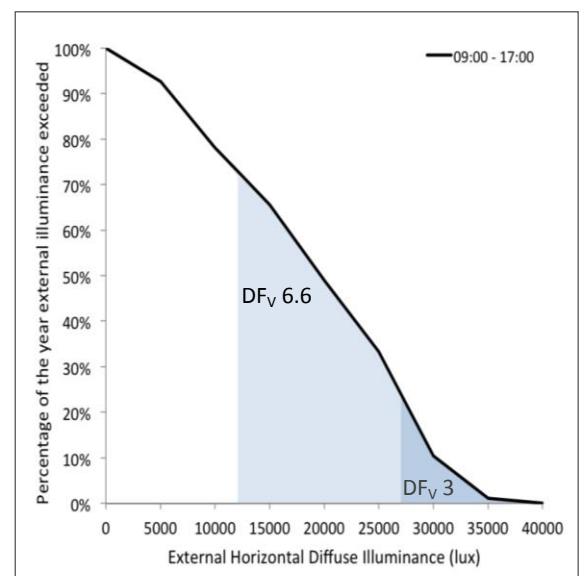


Figure 9.2: Annual external horizontal diffuse illuminance levels exceeded between 9am-5pm in Cardiff, UK and percentage of the year that the upper illuminance threshold of 800lux is exceeded based on a range of DF_V values

Figure 9.3 shows that at the eye level of a person within the room, this lower threshold level would be achieved for more than 90% of the year based on a DF_V value of 6.6 and the annual external diffuse illuminance in this location. In comparison, if a DF_V value of 3 was achieved then this lower illuminance threshold would be reached for 70% of the year. However if the DF_V value dropped to ≤ 1.0 this threshold of 370lux at the eye would not be achieved based on the availability of light between 9am and 5pm.

The upper illuminance threshold is only achieved for a significant percentage of the year based on the highest DF_V value of 6.6. It is not achieved for any percentage of the year based on a DF_V value less than 3 as shown in Figure 9.2.

9.1.2.2 External diffuse illuminance values for Helsinki

At a location such as Helsinki, Finland at latitude $60^{\circ}10'N$ the availability of daylight would be expected to change substantially throughout the year due to its position in relation to the sun. Winter months in particular offer very low levels of external diffuse illuminance across an average day. There is also a significant variation between available light during an average day in June and that of December which will therefore have an impact on the amount of light that reaches the building interior and in turn the occupant throughout the year. Figure 9.5 shows the percentage of the year that the external horizontal diffuse illuminance is exceeded between 9am and 5pm. As with Cardiff, the graph highlights the percentage of the year the lower illuminance threshold of 370lux will be exceeded based on a range of DF_V values.

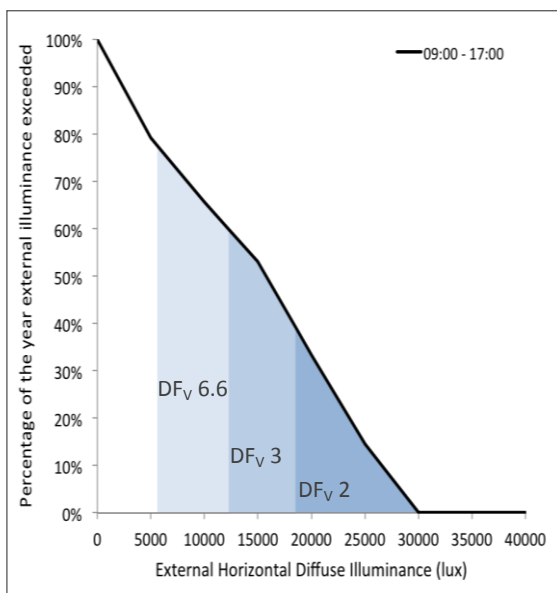


Figure 9.5: Annual external horizontal diffuse illuminance levels exceeded between 9am-5pm in Helsinki, Finland and percentage of the year that lower illuminance threshold of 370lux is exceeded based on a range of DF_V values

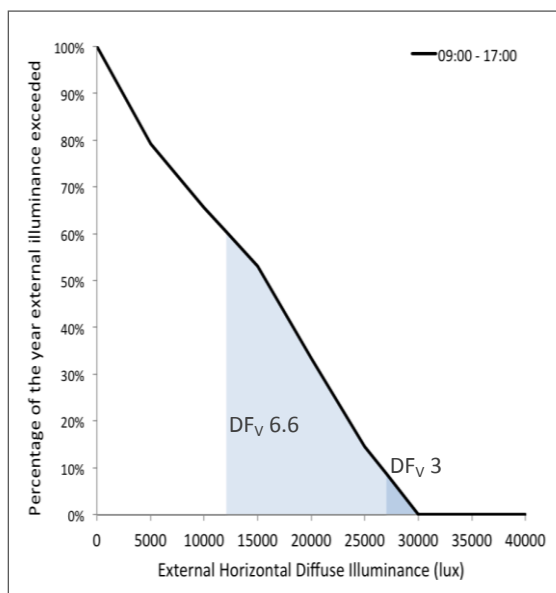


Figure 9.4: Annual external horizontal diffuse illuminance levels exceeded between 9am-5pm in Helsinki, Finland and percentage of the year that lower illuminance threshold of 800lux is exceeded based on a range of DF_V values

Based on the maximum DF_v value of 6.6 recorded in the Case Study room, it would be anticipated that in this location the proposed lower illuminance threshold value of 370lux will be reached for approximately 75% of the year. This DF_v value represents the best case scenario. If a DF_v value of 3 was achieved within the room this lower threshold of 370lux would be achieved for 60% of the year. If the lowest DF_v value of 0.6 achieved within the Case Study room is considered then this illuminance threshold of 370lux will not be reached based on this 9am-5pm period of the day.

Therefore to guarantee this lower threshold of 370lux is achieved a DF_v value of ≥ 1.5 would need to be achieved within the room based on the available external illuminance in Helsinki. If a position within the room achieved a DF_v value of ≥ 1.5 a person could expect to receive enough light at their eye level to stimulate circadian phase-resetting for approximately 15% of the year.

Figure 9.4 shows the percentage of the year that the upper illuminance threshold of 800lux for stimulation of circadian phase-resetting will be achieved on the DF_v values achieved in the Case Study room. It is evident from this graph that as in Cardiff this upper illuminance value will only be achieved for a significant percentage of the year based on the highest DF_v value of 6.6.

9.1.2.3 External diffuse illuminance values for Tangier

At latitude of 32°00N, external global illuminance levels in Tangier are consistently higher throughout the year than the other two locations. However, the maximum diffuse illuminance level achieved in Tangier, shown Figure 9.7 and Figure 9.6, is lower than that in Cardiff shown above. This is explained by the fact that, due to its climate, for the majority of the year the sky is clear in Tangier with a greater percentage of sunlight days in comparison to Cardiff. With less cloud cover there is less scattering of daylight therefore the diffuse component is reduced. Also due to its proximity to the equator, the length of daylight hours is short with the sun rising later and setting earlier on average than other more northerly locations throughout the year.

Figure 9.7 below shows the percentage of the year that the external horizontal diffuse illuminance is exceeded between 9am and 5pm. The graph also highlights the percentage of the year the lower illuminance threshold of 370lux will be exceeded based on a range of DF_v values. In comparison Figure 9.6 highlights the percentage of the year the upper illuminance threshold of 800lux will be exceeded.

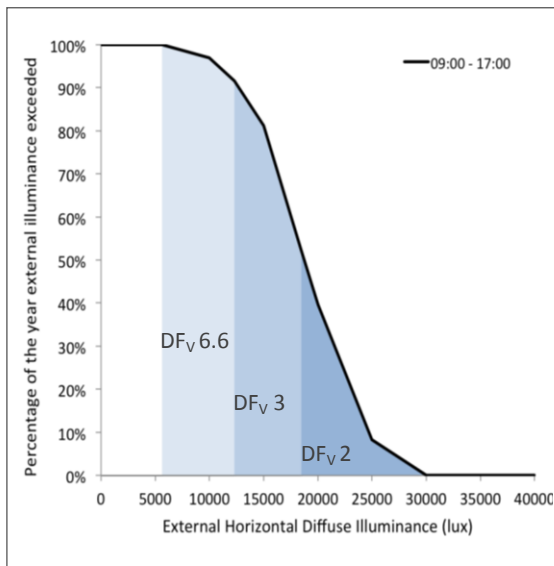


Figure 9.7: External horizontal diffuse illuminance levels exceeded between 9am-5pm in Tangier, Morocco and percentage of the year that lower illuminance threshold of 370lux is exceeded based on a range of DF_v values

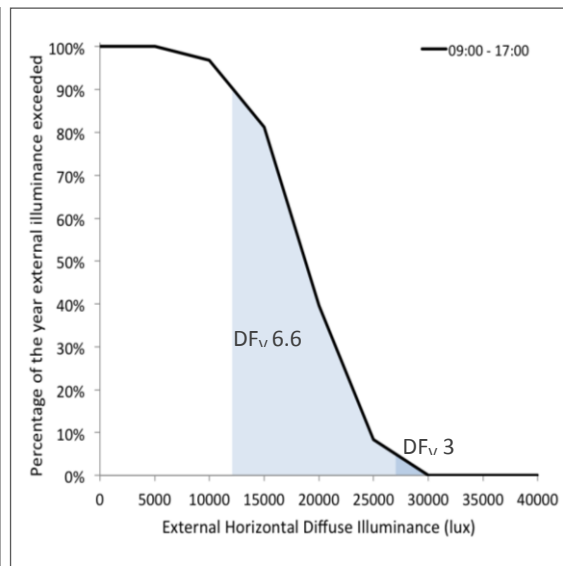


Figure 9.6: External horizontal diffuse illuminance levels exceeded between 9am-5pm in Tangier, Morocco and percentage of the year that lower illuminance threshold of 800lux is exceeded based on a range of DF_v values

Based on DF_v value of 3 achieved within the case study room it is likely that this illuminance threshold of 370lux would be achieved for more than 90% of the year. The maximum DF_v value measured in the case study room was 6.6, at these positions within the room it is likely that this lower threshold would be achieved for 100% of the year between the hours of 9am and 5pm.

Looking at the upper illuminance threshold of 800lux shown in Figure 9.6, this would be achieved for up to 90% of the year based on the highest DF_v value of 6.6. However, based on a DF_v value of 1 this upper illuminance threshold would not be achieved at all across the year during this period of the day therefore to guarantee this upper illuminance threshold is achieved the DF_v value would have to be ≥ 3 .

9.1.2.4 Summary of the effect of geographical location

It is clear that against possible expectations, the maximum diffuse illuminance level achieved in Tangier is lower than in Cardiff. This is explained by the fact that, due to its climate, for the majority of the year the sky is clear in Tangier with a greater percentage of sunlight days in comparison to Cardiff. In comparison in Cardiff, for a greater percentage of the year the sky is overcast with partial or complete cloud cover. As described in Chapter 5, with an increased amount of cloud cover there is also an increased amount of diffuse light due to scattering by water particles in the clouds.

If this evaluation had used global horizontal illuminance as the measure of available daylight the external illuminance in Tangier would have been significantly greater than in Cardiff. The difference between direct and diffuse horizontal illuminance as a percentage of global horizontal illuminance is shown in Table 9.3.

Table 9.3: Annual direct and diffuse horizontal illuminance as a percentage of global horizontal illuminance based on data extrapolated from *SATEL-LIGHT*

	Direct illuminance as % of global illuminance	Diffuse illuminance as % of global illuminance
Cardiff	36	64
Helsinki	38	62
Tangier	67	33

Table 9.3 shows that, when comparing the contributions of the direct and diffuse components of the annual global horizontal illuminance for Cardiff and Tangier, they are almost the exact opposite to each other. The direct illuminance component in Tangier provides almost 70% of the global illuminance whereas in Cardiff and Helsinki the diffuse illuminance component provides approximately 60% of the global illuminance.

Although the diffuse horizontal illuminance values, used in this thesis, provide a useful comparison of the effect of location and glazing specification on vertical illuminance levels achieved within a building interior, it is important to note that if buildings get significant access to direct light these internal illuminance levels will be higher, particularly in Tangier.

9.1.3 Time of day

As described in Chapter 4 and recorded in Table 9.1 above, biomedical research suggests that there is also an important temporal element to the lighting requirements of the non-visual system (Jewett, Rimmer, Duffy, Klerman, Kronauer, & Czeisler, 1997) (Wehr, Aeschbach, & Duncan Jr, 2001) (Khalsa, Jewett, Cajochen, & Czeisler, 2003). It is therefore valuable to establish the typical external diffuse illuminance levels available at specific times of day. For example, the most effective time of day to stimulate or entrain the human circadian system with light stimulus was shown to be during the early morning between 6-10am. If the external diffuse illuminance data for a particular location is filtered based on this reduced period of the day, it will provide a more accurate assessment of the potentially available daylight at the most effective time of day for this particular non-visual response to light.

The following section will look at the percentage of the year each location will achieve the lower illuminance threshold for each non-visual response based on the period of the day that has been shown to be most effective. This will be based on the range of DF_v values achieved within the Case Study room.

9.1.3.1 Effect of time of day on external diffuse illuminance in Helsinki

Looking at Helsinki, which has the lowest annual external diffuse illuminance levels across the three chosen locations; it is possible to establish the effect of filtering this climate data based on a shorter period of the day. This section will provide an overview of the early morning between 6-10am shown to be effective for circadian phase-resetting and the afternoon between 12-5pm shown to be effective for subjective alertness.

Time of day: 6 – 10am – circadian entrainment

Figure 9.8 shows the percentage of the year that the external horizontal diffuse illuminance is exceeded for this period of the morning between 6-10am, shown to be most effective for circadian entrainment. It also highlights the percentage of the year the lower illuminance threshold of 370lux will be exceeded based on a range of DF_v values.

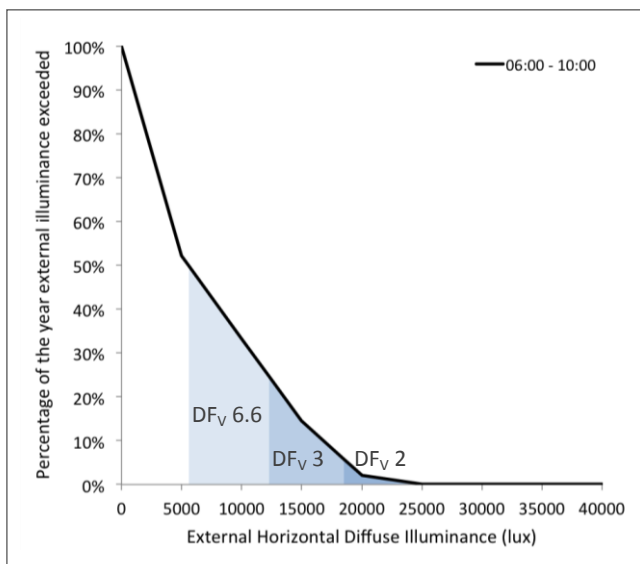


Figure 9.8: Annual external horizontal diffuse illuminance levels exceeded between 6-10am in Helsinki, Finland and percentage of the year that lower illuminance threshold of 370lux is exceeded based on a range of DF_v values

Due to its latitude there is a significant reduction in available external diffuse illuminance during the winter months in Helsinki. The hours of daylight are also reduced as the sun rises later in the morning and sets earlier in the afternoon. As is evident in Figure 9.8 this reduces the annual external diffuse illuminance, in particular during this period of the early morning. At the positions within the Case study room which achieved DF_v value of 6.6 the proposed lower illuminance

threshold of 370lux would be expected to be reached for approximately 50% of the year. When the DF_v values are ≤ 2 this lower illuminance threshold of 370lux will only be achieved for 5% or less of the year during this time of day.

Time of day: 12-5pm – Subjective alertness

The annual horizontal illuminance data can also be narrowed to show the percentage of the year that an external diffuse illuminance level is achieved between 12:00 – 17:00, the period of the day shown to be most effective for stimulating subjective alertness.

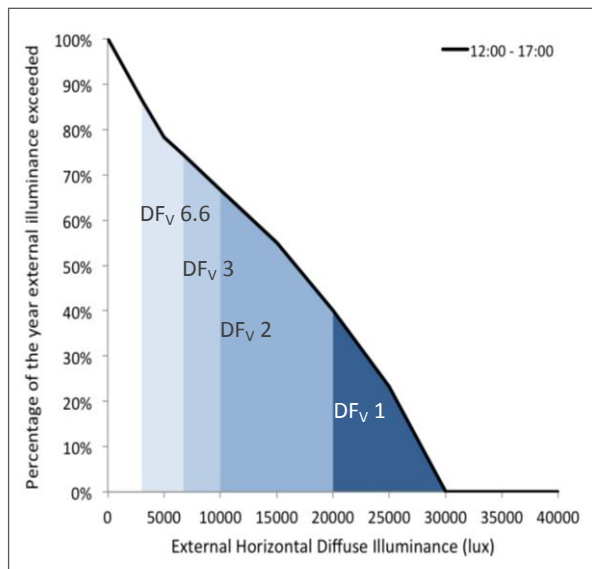


Figure 9.9: Annual external horizontal diffuse illuminance levels exceeded between 12-5pm in Helsinki, Finland and percentage of the year that lower illuminance threshold of 200lux is exceeded based on a range of DF_v values.

Figure 9.9 shows the percentage of the year external horizontal diffuse illuminance is exceeded during this period of the day. It also highlights the percentage of the year the lower illuminance threshold of 200lux for stimulation of this non-visual response will be exceeded based on a range of DF_v values.

Figure 9.9 highlights that the proposed lower illuminance threshold of 200lux would be achieved within the Case Study room for 85% of the year based on a DF_v value of 6.6. If this reduces to a DF_v value of 1 this lower illuminance threshold will

only be achieved for 40% of the year. For the internal illuminance level to reach the upper threshold of 840lux a DF_v value of ≥ 3 across the room would need to be achieved, however this would only be reached for 2% of the year.

9.1.3.2 Effect of time of day on external diffuse illuminance in Cardiff

Based on the climate data for Cardiff, UK it is possible to establish the availability of daylight across the year during these specific times of the day. As with Helsinki, in the section above, an overview of the early morning period between 6-10am and the afternoon between 12-5pm will be shown below.

Time of day: 6 – 10am – circadian entrainment

Figure 9.10 below shows the percentage of the year that external horizontal diffuse illuminance levels are exceeded during this early morning period of the day.

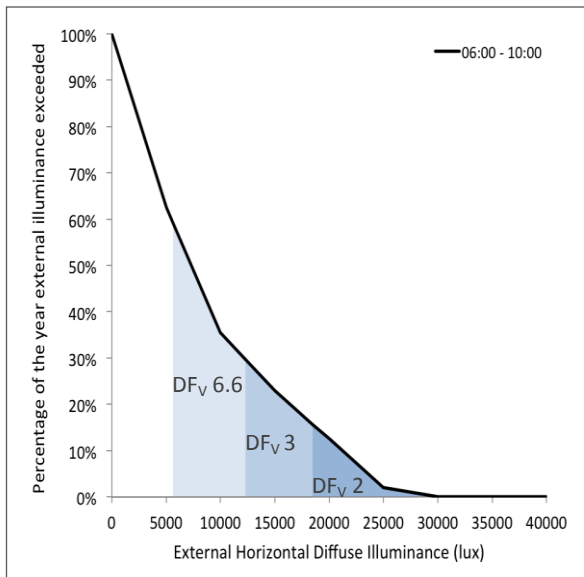


Figure 9.10: Annual external horizontal diffuse illuminance levels exceeded between 6-10am in Cardiff, UK and percentage of the year that lower illuminance threshold of 370lux is exceeded based on a range of DF_v values

If a DF_v value ≥ 6.6 was achieved within the Case Study room then this lower illuminance threshold of 370lux at the eye would be achieved for approximately 55% of the year based on the available external illuminance in Cardiff. As the DF_v value reduces to 3 this threshold would only be achieved for approximately 30% of the year. However the lowest DF_v value of 0.6 measured within the case study room would not provide the necessary illuminance level to achieve the lower threshold for stimulating circadian phase-resetting for any percentage of the year during this period of the day. DF_v values

between 2.0 and 1.5 would achieve the lower illuminance threshold for circadian phase-resetting for $\leq 10\%$ of the year.

Time of day: 12-5pm – Subjective alertness

By filtering the annual external illuminance data for Cardiff based on a 12-5pm period of the day it is possible to establish the external illuminance available as shown in Figure 9.11.

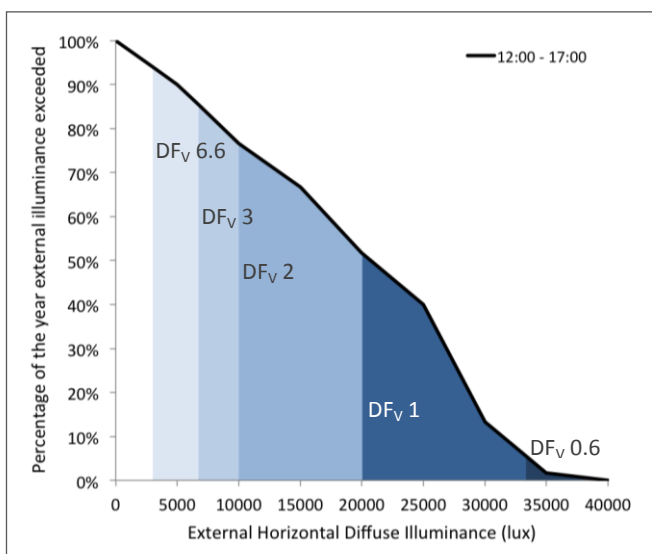


Figure 9.11: External horizontal diffuse illuminance levels exceeded between 12-5pm in Cardiff, UK and percentage of the year that lower illuminance threshold of 200lux is exceeded based on a range of DF_v values

Taking the proposed lower threshold value for stimulation of this human non-visual process of 200lux, Figure 9.11 also highlights the percentage of year when this illuminance level will be achieved based on the DF_v value within the example room. If a DF_v value of ≥ 3 was achieved at a given position within the room then the lower threshold of 200lux would be reached for almost 90% of the year during this period of the day.

However if the DF_v value reduced to just 0.6 then this lower threshold illuminance level would only be achieved for approximately 4% of the year.

9.1.3.3 Effect of time of day on external diffuse illuminance in Tangier

Due to its latitude the length of day in Tangier is fairly consistent across the year only reducing slightly during the winter months. This means that there is less variation across the year as is seen in more northerly locations such as Helsinki.

Time of day: 6 – 10am – circadian entrainment

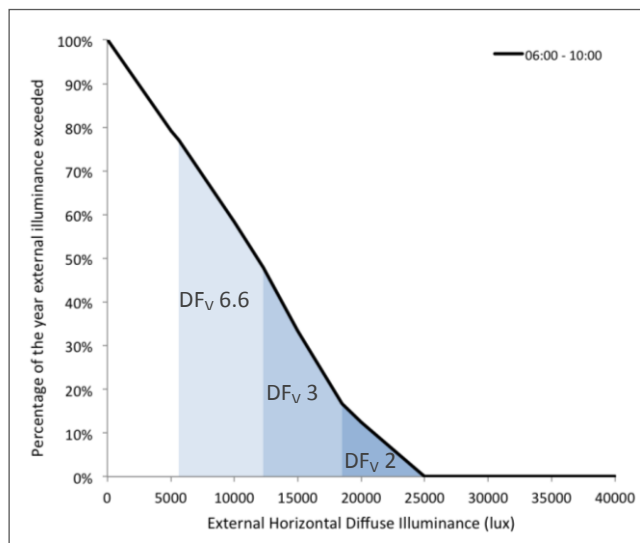


Figure 9.12: Annual external horizontal diffuse illuminance levels exceeded between 6-10am in Tangier, Morocco and percentage of the year that lower illuminance threshold of 370lux is exceeded based on a range of DF_v values

Figure 9.12 shows the percentage of the year in which the external horizontal diffuse illuminance is exceeded during the early morning period of the day shown to be most effective for circadian phase-resetting. Figure 9.12 also highlights the percentage of the year that the proposed lower illuminance threshold of 370lux required to stimulate this non-visual response would be achieved based on a range of DF_v values measured within the Case study room. To achieve this lower

illuminance threshold the DF_v value within the room would have to be >1.5 and at a DF_v value of 2 this illuminance level would only be achieved for approximately 15% of the year. If a DF_v value of 6.6 was achieved, the maximum value measured within the Case Study room, this illuminance level would be achieved for more than 75% of the year.

Time of day: 12-5pm – Subjective alertness

Figure 9.13 shows the percentage of the year the external diffuse illuminance is exceeded between 12-5pm in the afternoon. This is the period of the day that has been suggested as the most effective to stimulate alertness through light stimulus. The lowest measured DF_v value within the Case Study room was 0.6; based on the external diffuse illuminance during this period of the day in this location these positions within the room would not achieve the 200lux lower illuminance threshold.

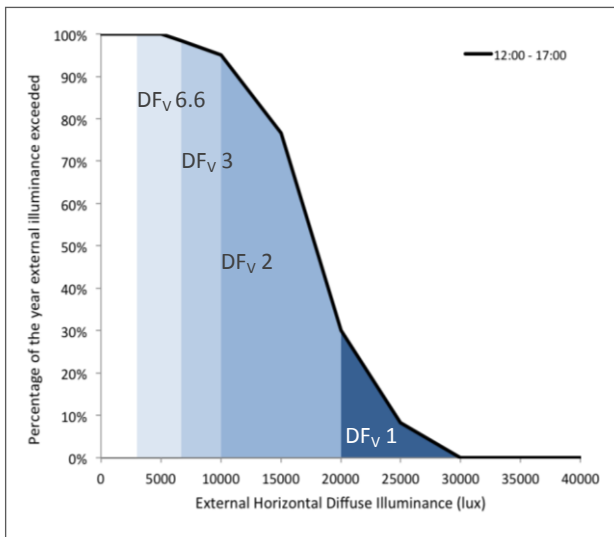


Figure 9.13: External horizontal diffuse illuminance levels exceeded between 12-5pm in Tangier, Morocco and percentage of the year that lower illuminance threshold of 200lux is exceeded based on a range of DF_v values

A minimum DF_v value of ≥ 0.8 would have to be achieved within the room for the illuminance level to reach this value. At positions within the room where the DF_v value reaches 1.0 then this lower illuminance threshold would be achieved for 30% of the year. If the DF_v value was ≥ 3.0 then this lower threshold would be achieved for almost the entire year during this period of the day. In order to achieve the upper threshold of 840lux the DF_v value would need to be >3.0 . At a DF_v value of 6.6 this upper illuminance threshold would be achieved for almost 90% of the year.

9.1.3.4 Summary of the effect of time of day

This assessment shows how the time of day affects whether a specific lighting environment provides enough light to stimulate non-visual processes of the people inhabiting the space. As outlined in Chapter 4 there are specific times of day when light stimulus is most effective for different non-visual processes, such as the early morning for circadian entrainment. However, this requirement may not always align with the available external diffuse illuminance due to the geographical location of the building. A summary of this is shown in Table 9.4 and Table 9.5.

Table 9.4: Percentage of the year between 6-10am the circadian rhythm entrainment illuminance thresholds are reached based on location and DF_v values

	Helsinki			Cardiff			Tangier		
	DF_v 1	DF_v 2	DF_v 6.6	DF_v 1	DF_v 2	DF_v 6.6	DF_v 1	DF_v 2	DF_v 6.6
370lux	0%	5%	50%	0%	12%	50%	0%	15%	75%
800lux	0%	0%	20%	0%	0%	30%	0%	0%	50%

Table 4 shows the percentage of the year between 6-10am that both upper and lower illuminance thresholds are achieved to stimulate circadian phase-resetting based on a range of

DF_V values. It shows that for a DF_V value of 1 neither illuminance threshold is met at any of the three locations.

Table 9.5: Percentage of the year between 12-5pm the alertness illuminance thresholds are reached based on location and DF_V values

	Helsinki			Cardiff			Tangier		
	DF _V 1	DF _V 2	DF _V 6.6	DF _V 1	DF _V 2	DF _V 6.6	DF _V 1	DF _V 2	DF _V 6.6
200lux	40%	65%	85%	50%	75%	95%	30%	95%	100%
840lux	0%	0%	60%	0%	0%	70%	0%	0%	90%

Table 9.5 shows the percentage of the year between 12-5pm that both upper and lower illuminance thresholds are achieved to stimulate subjective alertness based on a range of DF_V values. This table shows that, based on a DF_V value of ≤ 2 being achieved within the Case Study room, although the lower threshold will be reached for 40% or more of the year the upper threshold will not be reached at all at any location.

The comparison of data in both these tables above shows that for the illuminance thresholds to be achieved in the early morning period a higher DF_V value will need to be achieved within an interior space. This lack of light at the correct time of day in turn puts greater demands on the design of the space to achieve a better light distribution and greater DF_V values; to do more with less. This therefore includes the specification of the building components which will have an impact on the penetration of daylight into the building interior, such as the glazing system.

9.2 Different glazing systems in the Case Study room

Chapter 8 established the impact of a range of physical attributes of the Case Study room on the light received at eye level such as the depth from window wall, the colour and reflectance values of the surfaces as well as the position of the person within the room. In order to answer the question posed by this thesis, that the specification of glazing has an impact on the light received by the building occupant and therefore their well-being, a range of glazing systems were also tested within this Case Study room. The glazing system within a building envelope is the threshold between outside and inside, allowing light to penetrate into the building interior but also acting as a filter. As Chapter 6 highlighted, the material characteristics of various components within a glazing system can have a significant impact on how it performs in particular on the total visible transmittance.

The existing windows in the Case Study room were clear double glazed units, this provides a good reference base from which to run a series of comparisons with other glazing types to see the impact on the distribution of daylight within the room. Using the virtual model of the Case Study room, created with *3ds Max Design* and calibrated against the physical measurements taken in the room, the impact of these changes on the light distribution within the room was simulated. Analysing this against the lighting requirements for the non-visual system set out in Table 9.1 above this will highlight any implications of the choice of glazing system on the well-being of people occupying this room.

The range of six different glazing systems identified in Chapter 7 were analysed within the *3ds Max Design* model. These glazing systems represent a range of standard glazing types typically used in the construction industry and available from mainstream glazing manufacturers. The performance data for these glazing systems was generated using *WINDOW6* based on centre-of-glass values and is outlined again in Table 9.6. For each glazing system a 16mm air filled cavity was assumed, this may be larger than typically used by some manufacturers for triple glazed units in particular but this was maintained throughout for consistency. A nominal thickness of 6mm for each pane of glass was also maintained across all the glazing systems.

Table 9.6: Performance characteristics of a range of standard glazing products evaluated within the virtual case study room

No.	Glazing description	Tvis	Rfvis	Rbvis	Tsol	SHGC	LSG
0	Double Clear (reference)	0.82	0.1	0.1	0.7	0.7	1.1
1	Double LowE	0.61	0.1	0.11	0.23	0.2	2.5
2	Double Solar Control	0.57	0.12	0.08	0.34	0.4	1.5
3	Double Blue tinted	0.48	0.08	0.13	0.28	0.3	1.6
4	Triple LowE	0.48	0.26	0.26	0.22	0.3	1.8
5	Triple Blue tinted + LowE	0.4	0.11	0.19	0.21	0.2	1.6
6	Triple Bronze tinted	0.39	0.11	0.19	0.3	0.4	1.1

The chosen glazing systems provide a range of total visible transmittance values as well as a range of spectral selectivity shown by the LSG value (Light-to-Solar Gain). If sample #0 (Double Glazed Clear) is assumed to be the reference system and its visible transmittance value of 0.82 taken as 100%, the transmittance values of the other samples can be expressed as a percentage of this reference sample. For example, sample #6, the Triple Glazed unit with Bronzed tinted external pane provides 48% of the total transmittance provided by the Double Clear system which can be calculated from the data presented within Table 9.6.

As the total transmittance value decreases within this range of glazing systems it is plausible to assume the DF values achieved across the space will reduce by a similar percentage. The performance of these glazing systems within the case study room and the impact on daylight distribution was simulated. Both horizontal and vertical illuminance measures were used to establish any difference between the two. Looking at this comparison of the DF_H values, the traditional way of looking at DF values, for the range of glazing samples within the Case Study room shown in Figure 9.14 the reduction in horizontal DF values across all the samples is clear.

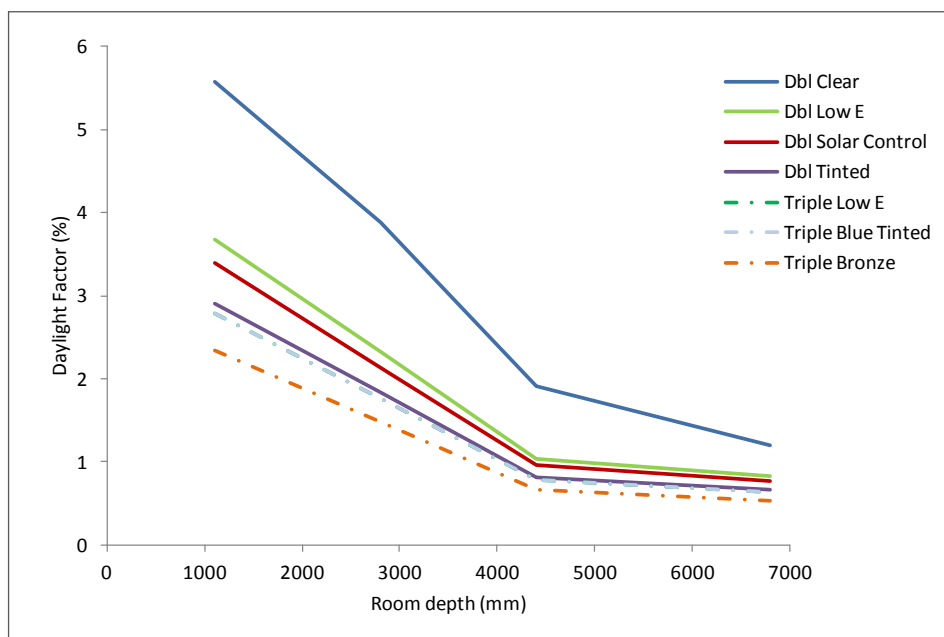


Figure 9.14: Graph showing a comparison of DF_H values across the depth of the Case Study room based on a range of different glazing systems

The average DF_H values for sample #6, Triple Bronze tinted, show a reduction in light distribution from the Double Clear reference glazing of 60%. This is in comparison to the stated total visible transmittance value shown in Table 9.6 which suggests that there is a 52% reduction in light transmittance between the two glazing system. Taking into consideration all the glazing samples there is a reduction in DF_H values in comparison to the reference glazing system of between 34-58%, this is in comparison to 26-52% reduction based on the stated visible transmittance set out in Table 9.6. This highlights that the stated visible transmittance values will not provide the complete picture of the effect of the glazing system on the distribution of light across an interior space.

Looking at all the horizontal DF values there is a variation of between 0.3-1.2% across the depth of the room. This highlights that based on horizontal illuminance measurements, the percentage reduction in light distribution between the glazing samples and the reference glazing across the room remains similar. This emphasises what might be an obvious assumption that although the specification of a glazing sample has an impact on the amount of light that penetrates an internal space it does not significantly alter the distribution of light around the room when measured on the horizontal plane. It is considered that this is due to the fact that the biggest contribution to the illuminance on a horizontal surface within a room will be the direct light from the window; the total transmittance value will therefore have the most significant impact in comparison to contribution from reflections from internal surfaces.

Table 9.7: Comparison of percentage reduction in transmittance for all glazing samples against the reference sample based on stated transmittance values and measured DF values.

	Percentage reduction from reference glazing sample (Double Glazed Clear)					
	Dbl LowE	Dbl Solar	Dbl Blue	Trpl LowE	Trpl Blue LowE	Trpl Brnz
Based on stated T_{vis}	26%	30%	41%	41%	51%	52%
Based on DF_H	38%	42%	51%	52%	59%	60%
Based on DF_V	41%	45%	53%	55%	61%	62%

Table 9.7 shows a comparison of the percentage reductions in transmittance between the stated total visible transmittance of each glazing system and the average horizontal and vertical DF values based on measurements within the case study room. This table shows that across this range of glazing systems there is between 10-15% variation between the stated visible transmittance values and the average vertical DF values. It also shows that the Double Glazed systems present the greatest variation.

In comparison with the reference glazing sample (#0) there is an average reduction in DF_V values of between 41-62% across the other glazing samples. The vertical DF values present a slightly greater reduction in transmittance in comparison to the reference glazing sample than was seen with the horizontal DF values. This table emphasises that the total visible transmittance values of glazing systems alone do not always provide a clear picture as to how much light will reach the eye level of a person within an internal space.

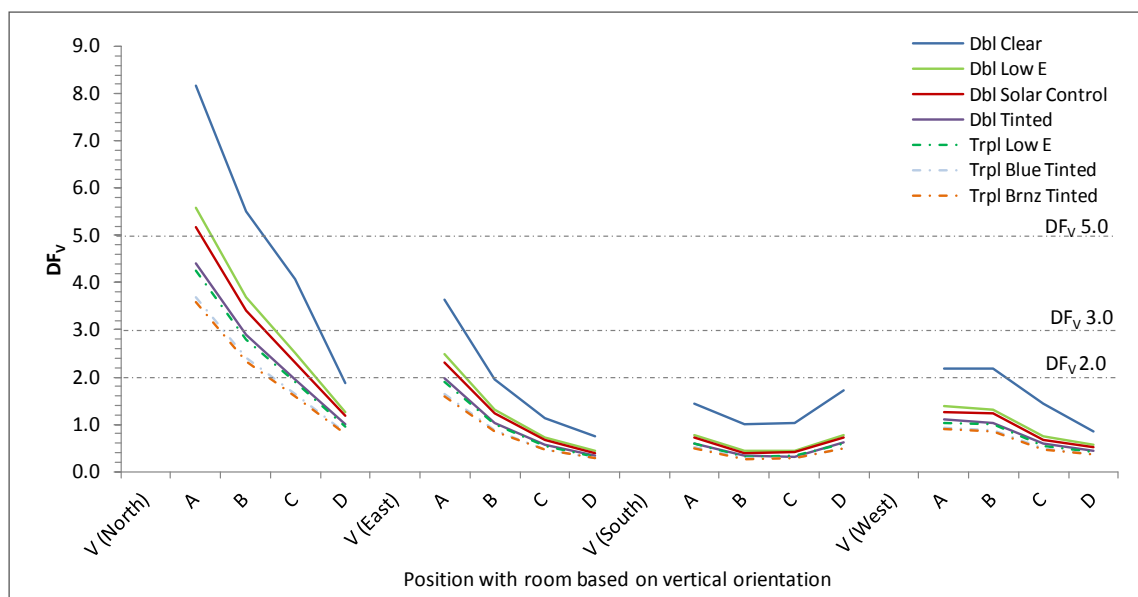


Figure 9.15: Comparison of all DF_V values facing in all orientations across the depth of the Case Study room based on a range of different glazing systems

Figure 9.15 shows the vertical DF values for all measurement positions across the Case Study room based on the stated range of glazing systems. Although the profile of this reduction in light transmittance from the reference glazing sample is similar across the depth of the room, it does vary between 6-10% depending on the glazing system. This is a more significant variation than was seen with the horizontal DF values described above. With the exception of the south facing position, the DF_v values in all orientations significantly reduce towards the back of the room.

The effect of the depth of the room was discussed in Chapter 8 but this graph shows that the reduction in DF_v values across the depth of the room is not completely consistent. The most significant variation is seen for all glazing types at position C which is 4.4m from the window. This could describe the depth at which the penetration of direct light from the window significantly reduces.

Figure 9.15 also identifies that, with the exception of the Double Clear glazing, this range of glazing systems struggles to achieve a DF_v value of 2 at any point of the room unless a person is facing the window.

9.2.1.1 Analysis of effect of glazing types using an assumed external illuminance of 10,000lux

This section will use an assumed illuminance of 10,000lux in order to make a clear evaluation of the effect of the specification of glazing on the distribution of daylight within the case study room. Based on the climate data provided by *SATEL-LIGHT* an external diffuse illuminance of 10,000lux would be expected at the three geographical locations outlined above for $\geq 65\%$ of the year during a typical working day. This therefore provides a realistic scenario within which to compare the impact of the stated range of glazing systems.

With this assumed external diffuse illuminance of 10,000lux it is possible to derive the vertical Daylight Factor values it is necessary to achieve internally in order to reach the lower and upper threshold ranges for the two non-visual responses to light outlined above. For example, a DF_v value of 3.7 would be needed to achieve the lower threshold for circadian phase-resetting of 370lux. In comparison a DF_v of 8 would be needed in order to reach the upper threshold of 800lux. In terms of stimulation of subjective alertness in order to achieve the lower illuminance threshold a DF_v value of 2 would be necessary and a DF_v value of 8.4 would be needed to reach the upper illuminance threshold of 840lux at the eye of a person within the room.

Taking into consideration the reduction in light penetration based on both the glazing system as well as the characteristics of the room it is possible to establish the positions within the room that might not achieve the necessary illuminance threshold.

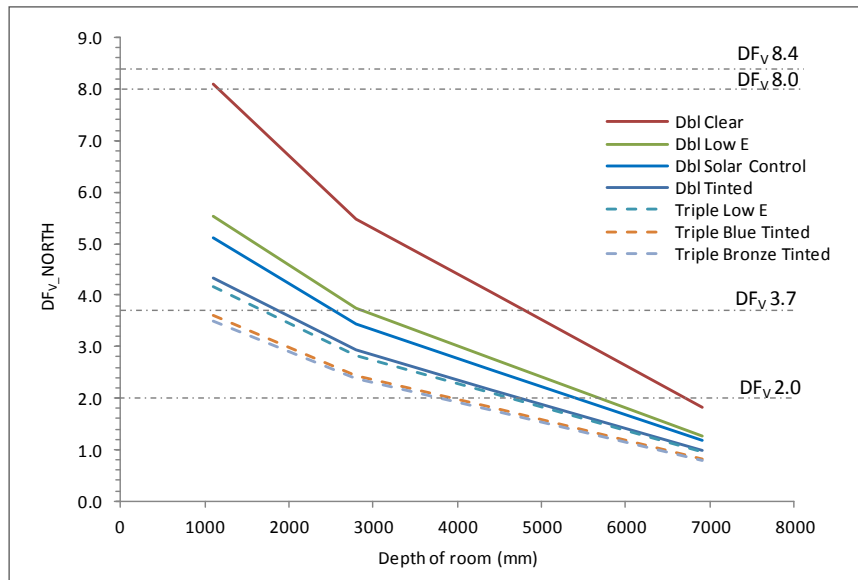


Figure 9.16: Comparison of DF_v _NORTH values (facing directly at window wall) across the depth of the example room based on a range of different glazing systems

Looking at the best case scenario of a person facing the window, as shown in Figure 9.16 and assuming an external illuminance of 10,000lux, the lower illuminance threshold of 370lux for circadian phase-resetting would be achieved up to 1.2m into the room with 5 out of the 7 glazing samples. Neither the Triple Blue-tinted (sample #5) nor the Triple Bronze-tinted (sample #6) glazing systems would provide enough light into the room to achieve this lower illuminance threshold of 370lux. Beyond 3m from the window wall only the reference glazing system, the Double Clear system would achieve this lower threshold. At the furthest measurement point within the room, at 6.8m from the window, this threshold of 370lux would not be met by any of the glazing systems based on an external illuminance of 10,000lux. Only the Double Clear glazing would achieve the proposed upper illuminance threshold of 800lux for circadian phase-resetting and this would only happen at the seating position nearest the window.

Considering now the proposed lower illuminance threshold to stimulate subjective alertness of 200lux, up to approximately 3.5m into the room all seven glazing systems would provide enough light to achieve this illuminance level based on an external illuminance of 10,000lux. Beyond this distance into the room the DF_v values drop off such that at 5.5m from the window wall only the Double Clear glazing reference system would achieve the necessary illuminance

level. None of the glazing systems would provide enough daylight to reach the upper illuminance threshold of 840lux based on the assumed external illuminance of 10,000lux. The ability of this lighting environment to stimulate these non-visual processes heavily depends on the glazing type as well as the distance of the person from the window wall even in this best case scenario with a person facing the window.

As shown in Chapter 8, the orientation of a person within the Case Study room or the direction they are facing has a significant impact on the light received at their eye level. This study of the effect of the choice of glazing has also been shown to have a specific effect in relationship to the orientation or direction of view. This was shown clearly across all four orientations in Figure 9.15 above and is shown in more detail for DF_{V_EAST} in Figure 9.17.

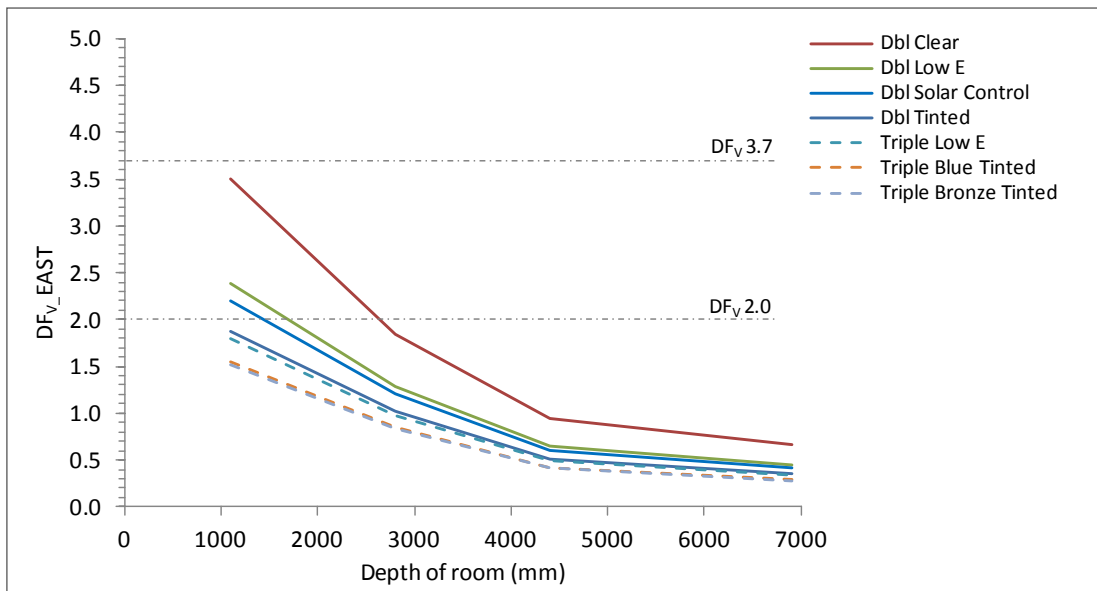


Figure 9.17: Comparison of DF_{V_EAST} values (facing the East wall) across the depth of the example room based on a range of different glazing systems

Figure 9.17 shows that there is a variation between DF_V values for the range of glazing samples in comparison to the reference system across the room of $\pm 2\%$. This was particularly evident with sample #3 (Dbl Blue Tinted), sample #4 (Tpl LowE) and sample #6 (Tpl Brnz Tinted), whereas the other samples produced more consistent results. It is acknowledged that this does represent a small variation but highlights that there is a relationship between the glazing system and orientation in some instances. It is considered that this may be due to the colour and reflectance values of the surfaces within the room, a design parameter also highlighted in Chapter 8 as having an impact on light distribution.

Looking at the glazing systems that showed the greatest variation in this orientation, those that included body-tinted glass it might suggest that there is a more significant relationship between the light transmitted by these systems and the colour and materiality of surfaces within the room. As discussed in Chapter 6 each glazing system interacts differently with different parts of the visible spectrum, absorbing, reflecting or transmitting light. This is particularly evident for body tinted or coated glass as the inherent transmittance properties of the glass substrate has been altered. A more detailed spectrum analysis would be necessary to ascertain whether the spectral distribution of the light transmitted by these glazing samples is the cause of a reduction in light in this orientation.

Table 9.8: Comparison of percentage reduction in transmittance for all glazing samples against the reference sample based on orientation.

Glazing sample	Percentage reduction from reference glazing sample (Double Glazed Clear)			
	DF _V _NORTH	DF _V _SOUTH	DF _V _EAST	DF _V _WEST
DbI LowE	34	53	36	40
DbI Solar Control	39	57	41	45
DbI Blue Tinted	48	65	49	52
TpI LowE	50	65	52	55
TpI Blue Tinted+LowE	57	70	58	60
TpI Bronze Tinted	58	71	59	61

Table 9.8 shows a comparison of the relationship between orientation and choice of glazing and the impact this has on the distribution of daylight within the Case Study room. This is particularly highlighted when looking at the measurements taken with an orientation facing away from the window wall towards the south wall of the room. All glazing samples presented a greater percentage reduction in comparison to the reference glazing sample than in any other orientation with a 10-15% variation across all glazing systems.

With the exception of the reference glazing, all the glazing samples used within this investigation have either a coated or tinted component to the system, which colour the light. Further work including a more detailed spectrum analysis of a range of glazing samples to establish whether the specification not only affects the amount of light being transmitted but also how it interacts with the surfaces of the room. This would be considered to be likely as colour has already been shown to be an important factor in light received at the eye in Chapter 8.

So having shown that glazing specification has an impact on the light that reaches the eye this section will now focus on two typically used glazing systems within more northerly northern hemisphere locations. Figure 9.18 shows all measurement positions within the room for Double Glazed LowE (sample #1) as well as Triple Glazed LowE (sample #4). This type of glazing system is typically used to improve the thermal performance of the building envelope by reducing heat loss from the building in particular.

The Double Glazed LowE system represents a 40% reduction in light distribution based on vertical DF values in comparison to the Double Clear reference glazing system. With an assumed external illuminance of 10,000lux this glazing system would provide a range of illuminance values at the eye level of a person sat within the room of between 40-560lux based on the DF_v values achieved within the Case Study room. At the upper end of this range it would be enough to stimulate the lower illuminance threshold of both non-visual responses but at the lower end it would be a long way off the light level necessary at the eye.

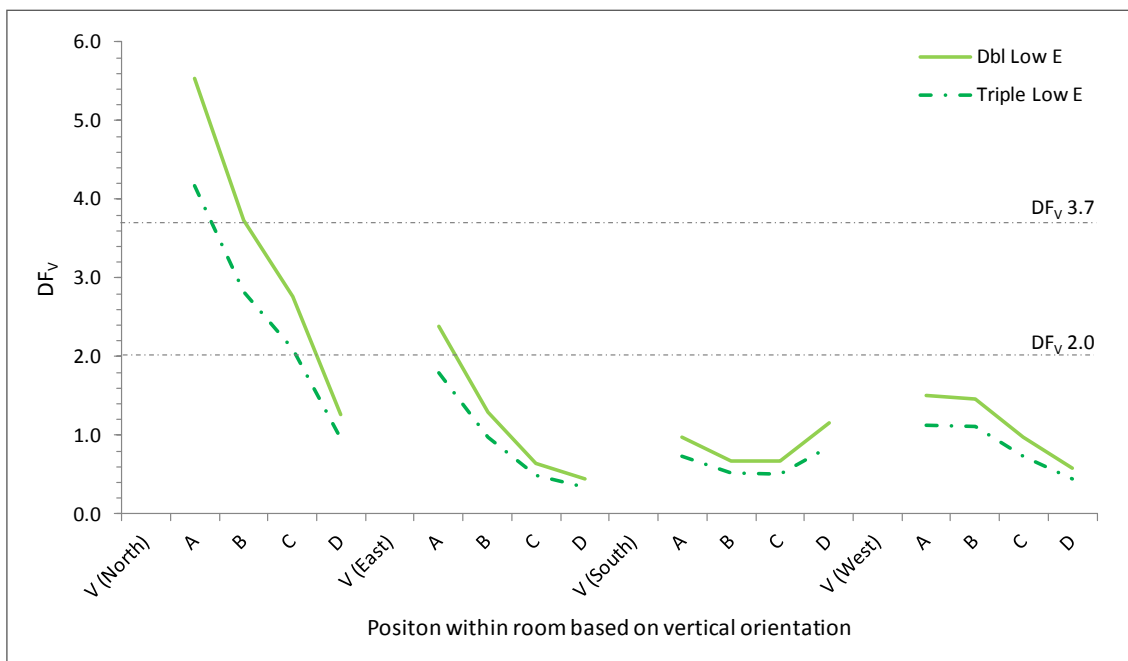


Figure 9.18: Comparison of DF_v values facing in all orientations across the depth of the example room based on glazing sample #1 and glazing sample #4 showing the lower illuminance thresholds for both non-visual response to light, 200lux and 370lux

Figure 9.18 shows a comparison of the DF_v values for the Triple Glazed LowE system (sample #4), a glazing system designed to provide similar performance characteristics as sample #1. It shows that there is a reduction in distribution of light between the two glazing systems of approximately 25%. Based on this assumed external illuminance of 10,000lux this glazing system would provide between 30-430lux at the eye level of a person within this room across all seated positions measured. As with the Double Glazed LowE system discussed above the

upper end of this range would be enough to stimulate the lower illuminance threshold for both non-visual processes but at the lower end it would not. Looking at Figure 9.18 it is clear that only if a person was sat facing the window in this case study room would they be likely to receive enough light at their eye to reach the lower thresholds for both non-visual responses based on an external illuminance of 10,000lux.

If all the glazing samples are compared across all the vertical measurement positions within the Case Study room the range of DF_v values achieved across the room was 0.3 - 8.0. Based on an assumed external illuminance of 10,000lux this would equate to a range of illuminance values received at the eye of between 30-800lux. This represents a wide range of potential light stimulus available to a person sat within the room. As a range this would achieve the lower threshold for both circadian phase-resetting and subjective alertness but it would only reach the proposed upper threshold illuminance for circadian phase-resetting of 800lux.

If the Double Clear system, the reference glazing sample, was excluded the range of potential illuminance available would reduce to between 30-560lux. At the higher end of this range of illuminance levels, a person sat within this room would receive enough light to stimulate the lower threshold for both non-visual responses. However at the lower end of the range the illuminance level would be significantly below the proposed lower threshold. This evaluation has shown that whether a person receives enough light at their eye would be significantly affected by the chosen glazing system.

Although these illuminance ranges suggest that certain positions within the Case Study room would receive enough light to stimulate the non-visual responses, it is a wide range and does not give the complete picture in terms of the percentage of the room that would receive enough light. Table 9.9 gives an overview of the approximate percentage of the measurement positions within the Case Study room that achieve a range of vertical illuminance levels based on a range of different glazing systems analysed assuming that there is an external diffuse illuminance of 10,000lux.

Table 9.9: Percentage of room that exceeds stated illuminance level based on glazing samples tested and external diffuse illuminance of 10,000lux

Vertical Illuminance	Double Clear (%)	Double LowE (%)	Double Solar Control (%)	Triple LowE (%)	Triple Blue Tinted + LowE (%)	Triple Bronze Tinted (%)
50 lux	100	98	94	81	69	69
100 lux	75	56	56	38	25	25
200 lux	38	25	25	19	13	13
370 lux	19	13	6	6	0	0
800 lux	6	0	0	0	0	0
840 lux	0	0	0	0	0	0

The table above provides a picture of the impact of the chosen glazing system on illuminance levels likely to be achieved across the room. If a Triple Glazed unit with bronze-tinted external pane was installed into this Case Study room the lower illuminance threshold of 370lux for circadian phase-resetting at the eye of a person would not be achieved anywhere within the room. In comparison 13% of the measurement positions within the room would reach the lower illuminance threshold of 200lux for subjective alertness. With this glazing system neither upper illuminance threshold would be achieved at any point within the room.

In contrast using the Double glazed LowE system would increase the number of positions which achieve the lower illuminance threshold at the eye of a person within the room for circadian phase-resetting to $\geq 13\%$. This glazing system would also increase the percentage of the room that would achieve a vertical illuminance of 200lux to 25%. As with the Triple Bronze tinted glazing system the upper illuminance threshold would not be met at any point within the room based on an external illuminance of 10,000lux.

The Double Clear glazing system would achieve a vertical illuminance of 200lux to reach the lower illuminance threshold for subjective alertness across 38% of the Case study room and the lower illuminance threshold of 370lux for circadian phase-resetting across 19% of the room. This glazing system would also provide enough daylight within the room to achieve the upper illuminance threshold of 800lux for circadian phase-resetting across 6% of the room. It is the only glazing system that would achieve this vertical illuminance level based on an external diffuse illuminance of 10,000lux. The difference in daylight distribution based on the choice of glazing system can be clearly seen Figure 9.19.

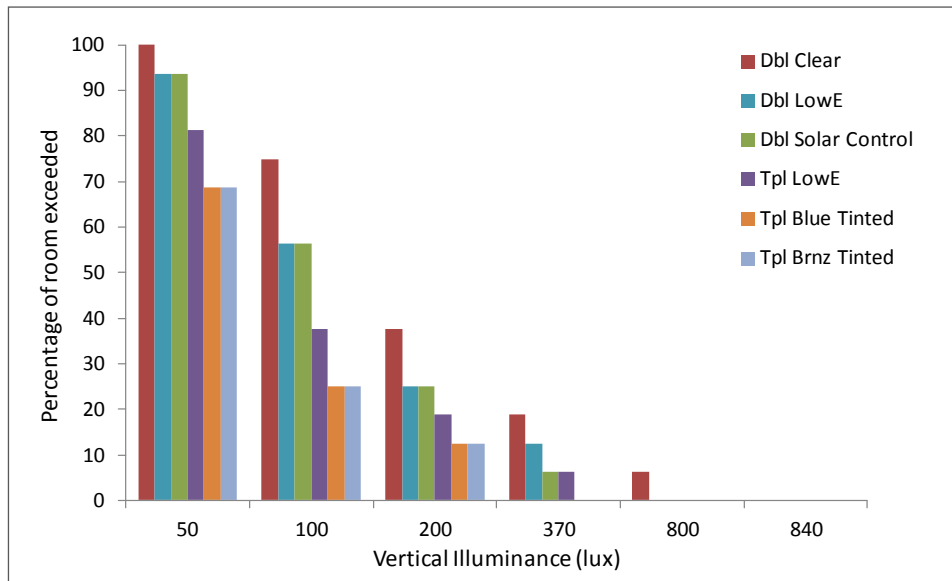


Figure 9.19: Percentage of room that exceeds stated illuminance levels based on glazing samples tested and external diffuse illuminance of 10,000lux

It is clear from the above study that the choice of glazing has a significant effect on the light distribution and the amount of light that reaches the eye level of a person sat within the case study room. As this assessment was undertaken using the physical parameters of the case study room it is not entirely clear the exact level of impact that the choice of glazing system is having. As was shown in Chapter 8 there are a number of parameters that effect daylight distribution within a space such as the depth of the room and the colour and materiality of the surfaces. In order to establish the overall impact of the glazing independent of these other variables a comparison of this range of glazing systems was undertaken against a test system that provided 100% transmittance. It was possible to undertake this analysis using the *3ds Max Design* software. All the surfaces within the case study room were set to white such that this variable was taken out of the calculation.

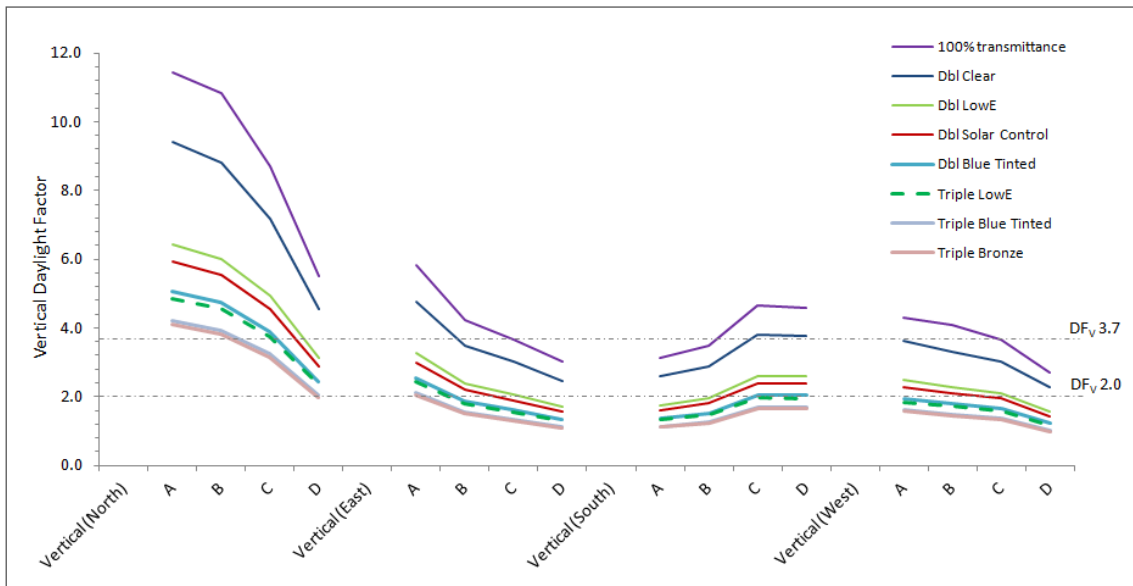


Figure 9.20: Comparison of all DF_v values for all orientations across the depth of the Case Study room based on a range of different glazing systems against a 100% transmittance test sample

Figure 9.20 shows that there is a clear impact of the choice of glazing with even the Double Clear glazing system presenting a reduction in daylight distribution. From this study it is possible to see that the choice of glazing system alone results in a reduction in daylight distribution of between 18-64% based on the range of glazing systems tested. If the glazing system with the highest visible transmittance value was considered the best in terms of achieving the necessary internal vertical illuminance, from the best to the worst glazing system there is a variation in average daylight distribution of approximately 57%.

Although this scenario where all the surfaces within the Case Study room are white is unrealistic it does provide an opportunity to assess the true impact of the choice of glazing on the distribution of daylight around the room. Based on the assumed external diffuse illuminance of 10,000lux it is possible to see in Figure 9.20 that with the exception of the vertical orientation facing the window only the 100% transmittance glazing sample and the Double Clear would provide the necessary illuminance to achieve both lower illuminance thresholds of 200lux and 370lux across the depth of the room.

9.2.2 Summary of the effect of glazing specification

These findings have shown that the choice of glazing system has a significant effect on the light that is received at eye level of a person sat within the Case Study room, in the context of both visual and non-visual requirements.

Based on the Case Study room, and compared to the Double Clear reference glazing system currently installed, changing the specification of the glazing system resulted in a reduction in vertical illuminance across this case study room between 41-62%. This highlighted the fact that the total visible transmittance values of glazing systems alone do not always provide a clear picture as to how much light will reach the eye level of a person within an internal space.

The Double Clear system, the original glazing system within the Case Study room, was the only glazing system which provided enough daylight to achieve the upper illuminance threshold of 800lux for circadian phase-resetting. Although a number of existing buildings are likely to have clear double glazed windows, due to an increase in energy reduction targets and a drive towards more thermally efficient building envelopes it is less common for these window systems to be installed in new buildings.

This study also emphasised that a number of these factors are interconnected as was also shown in Chapter 8. The relationship with the depth of the room and in turn the position of someone within the space and the amount of light that reaches them is well documented (Rennie & Parand, 1998) (CIBSE, 2012). However when considering the vertical illuminance the orientation of the person, the direction in which they are facing within the room and the glazing specification affects the light that reaches their eyes. It is considered that this effect is as a result of the relationship between the quality of light transmitted by each glazing system and the colour and materiality of the surfaces within the room. A more detailed analysis of this was outside the scope of this thesis and will form part of any further work.

When looking at the impact of glazing specification in isolation, the study highlighted that the glazing system chosen has an impact on the distribution of daylight between 18-64% based on the range of glazing systems tested. This is a significant effect in comparison to the other parameters of the room described in Chapter 8. It is a similar magnitude of effect to the colour of the walls, which can have up to a 40% impact on the distribution of daylight, and the orientation of a person within the space, which was shown to result in a reduction of daylight by up to 53% in comparison to the measured horizontal illuminance.

Although an assumed external illuminance of 10,000lux was used within this study to provide a means to quickly compare whether the range of glazing systems achieved the necessary internal illuminance, this does not provide a full account of the impact of the available external illuminance across the year at any given location, as shown in section 9.1.2. The next section

will take annual external diffuse illuminance of a given geographical location into consideration along with the specification of glazing.

9.3 Evaluation of all variables

This thesis has studied and shown the independent effects of varying a set of design parameters on the light distribution within a Case Study room, and the impact of these as a percentage variation between best and worst, within the range tested, is shown below:

- The colour of all room surfaces – 50% variation between best and worst
- The colour of the wall surfaces – 47% variation between best and worst
- The reflectance of the room's surface finishes – 22% variation between best and worst
- The direction of gaze of the occupant – 80% variation between best and worst
- The chosen glazing specification – 57% variation between best and worst
- The geographical location of the room – 18% variation between best and worst total diffuse light availability across the year.

This summary shows that although the orientation of a person within the Case Study room has the greatest effect on light received at the eye, in terms of the design parameters of the room the specification of glazing has the greatest impact on the light that reaches the eye of a person within the room. The colour of the room surfaces were also shown to have a significant impact although not quite as great as the specification of glazing.

In the studies above an assumed external illuminance of 10,000lux was used in order that the impact of the different parameters such as choice of glazing system could be compared. As discussed earlier external illuminance levels are not constant across a day or a season therefore one assumed value is not an accurate representation of the actual external illuminance available. In order to make a more detailed analysis of the effect of these design variables within a more realistic context it is necessary to make an assessment using annual external illuminance data based on a specific location.

This section will evaluate a number of glazing systems against average external illuminance data for three different Northern hemisphere locations; Cardiff, Helsinki and Tangier. Key attributes of the physical space that have been shown to have an impact on the distribution of daylight will also be included in the assessment, such as surface colour and depth of room discussed in Chapter 8.

The methodology used for this part of the study is as follows:

For each geographical location, a range of three glazing systems will be analysed; Double Glazed Clear, Double Glazed LowE and Triple Glazed LowE. These three glazing systems are

commonly used within the construction industry and therefore widely available from window manufacturers, they also provide a conservative range of visible transmittance values.

For each glazing system, two orientations or directions of view within the Case Study room will be assessed across the full depth of the case study room; facing the window represented by DF_{V_North} and facing away from the window represented by DF_{V_South} . These two orientations provide the best and worst case scenario in terms of daylight distribution based on the studies undertaken in Chapter 8. This covers the full range of light distribution that would be anticipated based on position of a person within the room.

Finally as the colour of the surfaces within the Case Study room were shown to have a significant impact on vertical illuminance levels, a range of five different wall colours will be assessed; white, light green (the original wall colour), cream, blue and red. These colours provide a range of colours in terms of hue and colour spectrum, they also represent a range of commonly used colours within internal spaces, whether as an accent wall or a full room.

These parameters will therefore make up a series of hypothetical rooms which will be assessed against the combined lower and upper illuminance thresholds, 200-840lux, for both non-visual responses to light outlined in Table 9.1 at the beginning of this Chapter. The average annual diffuse illuminance profile for each geographical location will be narrowed to a period of the day from 6am to 5pm to capture the two periods of the day, early morning and afternoon, highlighted above as effective for circadian phase-resetting and subjective alertness respectively.

This final assessment will establish whether the combination of key factors; glazing specification, colour of surfaces, orientation of a person within the space and the depth of room provide the necessary illuminance to stimulate these non-visual responses and in turn support well being of the occupant.

It is important to note that as discussed in Chapter 8, the virtual model of the Case Study room over-estimates the vertical DF values for the South orientation, facing away from the window. This is particularly evident at position D where the DF_V value is over-estimated by approximately 150% to the physical measurement taken in the room itself.

The following sections will look at the effect of these combined parameters in the three different geographical locations.

9.3.1.1 Effect of combined parameters within the Case Study room: Cardiff, UK

At the beginning of this section Figure 9.21 shows the percentage of the year a given illuminance level is exceeded between 6am and 5pm in Cardiff. The following figures, Figure 9.22 to Figure 9.27 show that in Cardiff the choice of glazing has a measurable impact on the ability of the room to provide the necessary illuminance to support both non-visual responses.

Figure 9.22 shows that when a person is facing the window the Double Glazed Clear system achieves both lower and upper illuminance thresholds, indicated by the dashed lines and solid lines respectively, across the depth of the room. The lower illuminance threshold will be met for between 80-90% of the year up to 4.5m into the room with all wall colours.

For Figure 9.23 onwards a short description is given alongside each graph.

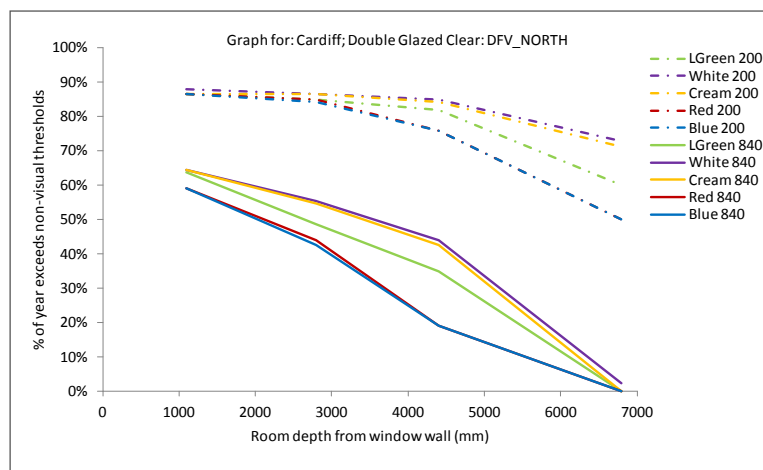


Figure 9.22: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

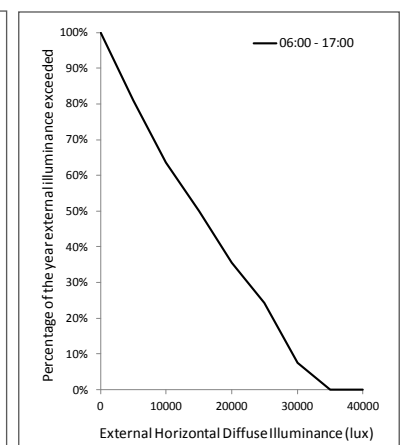


Figure 9.21: Percentage of year given horizontal diffuse illuminance exceeded between 6am-5pm in Cardiff

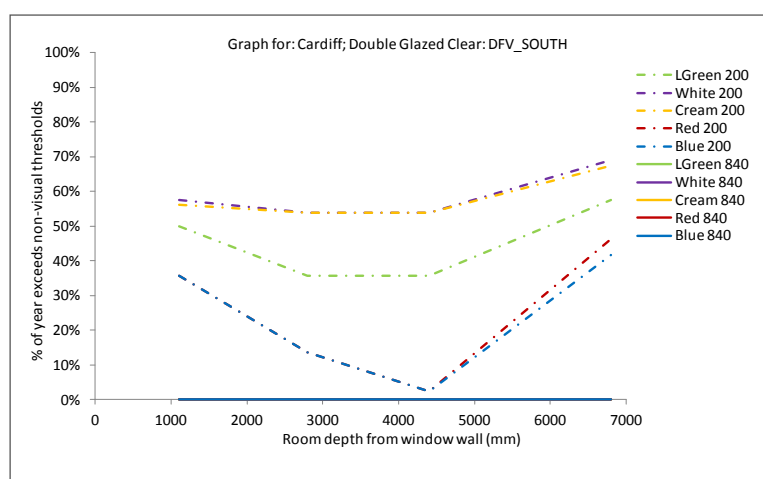


Figure 9.23: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

**Double clear glazing:
facing away from
window**

The lower threshold is achieved with all wall colours. Upper threshold is not achieved at all.

Figure 9.23 shows that, as there are no solid lines evident on the graph, with the Double Glazed Clear system when a person is facing away from the window the upper threshold of 840lux will not be achieved for any part of the year. In comparison the lower threshold of 200lux will be achieved for a varying amount of the year for all colour combinations. For example, based on the white and cream walls this lower illuminance threshold will be achieved for approximately 60% of the year across the depth of the room.

Double LowE glazing

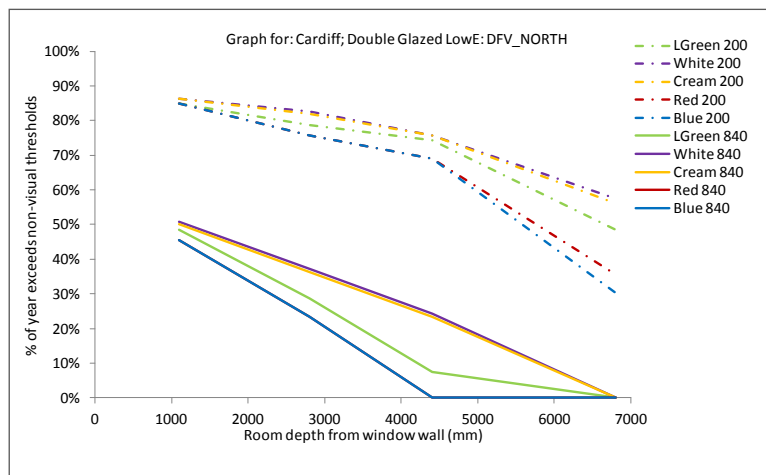


Figure 9.24: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

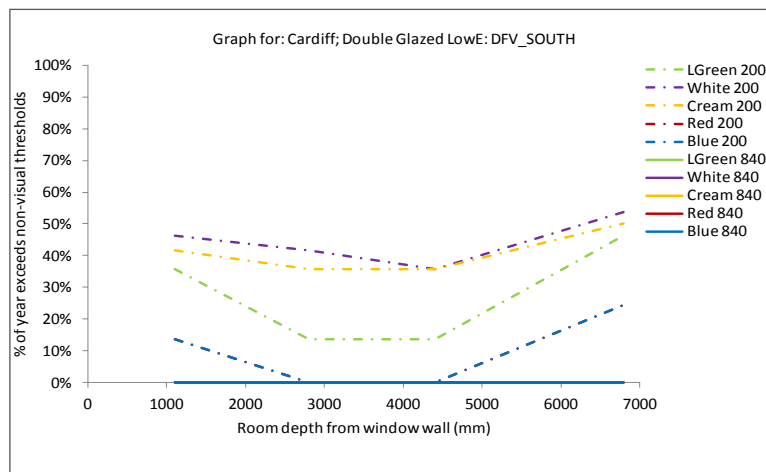


Figure 9.25: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Double LowE glazing: facing window

Beyond 4.5m from the window wall upper threshold will not be reached based on darker wall colour such as red and blue.

Double LowE glazing: facing away from window

Lower illuminance threshold achieved facing away from the window for approximately $\geq 15\%$ of the year with light wall colours.

Similarly to the Double Clear glazing the Double LowE glazing achieves both lower and upper illuminance thresholds when a person is facing the window shown in Figure 9.24. However with the darker coloured walls the upper threshold is only achieved up to approximately 4.5m into the room. With the Double LowE glazing the lower threshold is achieved for

approximately 70-85% with all wall colours when a person is directly facing the window, less than seen with Double Clear glazing. Figure 9.25 shows that the Double LowE glazing does not achieve the upper illuminance threshold when a person is facing away from the window. The lower illuminance threshold is achieved but only for less than 50% of the year for all wall colours when a person is facing in this direction.

Triple LowE glazing

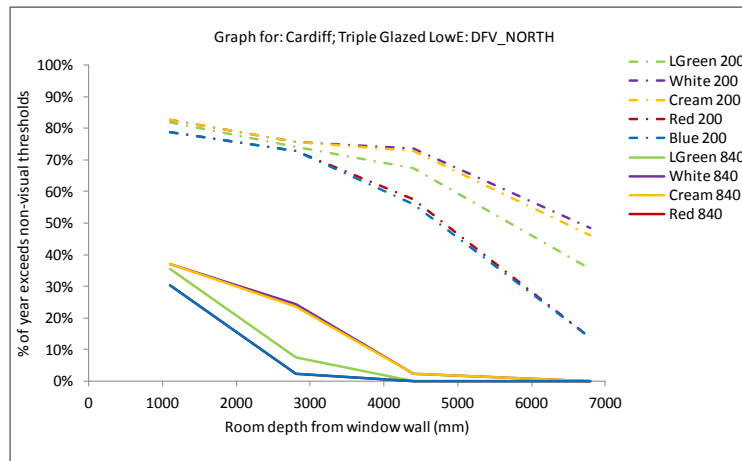


Figure 9.26: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

Triple LowE glazing:

facing the window

Both lower and upper thresholds achieved up to 2m from the window wall for approximately $\geq 15\%$ of the year.

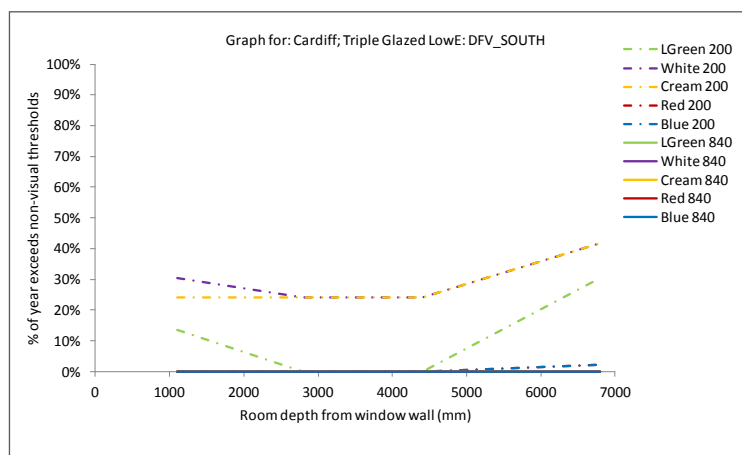


Figure 9.27: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Triple LowE glazing:

facing away from window

Lower threshold only achieved across the full room with white and cream walls.

Figure 9.26 shows that like the Double Glazed systems the Triple LowE glazing achieves both lower and upper illuminance thresholds when a person is directly facing the window. The upper illuminance threshold of 840lux is achieved up to 2m into the room for all wall colours but only achieved up to 4.5m into the room for the white and cream wall colours. Figure 9.27

shows that, as there are no solid lines on the graph, that when a person is facing away from the window the upper threshold is not reached for any percentage of the year. The lower threshold is also not achieved with the darker coloured walls and only achieved across the depth of the room for a maximum of 40% of the year with the white and cream walls.

In summary the study of the effect of the combined parameters based on the Case Study room in Cardiff shows that when a person is facing away from the window the upper illuminance threshold of 840lux will not be met with any of the glazing systems. This emphasises the impact of the orientation of a person within a room on the light that will be received at their eyes as discussed in Chapter 8. Both double glazed systems achieve the lower illuminance threshold of 200lux irrespective of the orientation, however when a person is facing away from the window, the Triple LowE glazing would only reach the lower illuminance threshold when the walls of the room were a lighter colour.

It is also evident that the Double Clear glazing, with a visible transmittance of 82%, is the most effective of the three glazing systems as might be anticipated. The study shows that this glazing system will achieve both lower and upper illuminance thresholds across the depth of the room irrespective of wall colour when a person is directly facing the window. If a person is facing away from the window it maintains the lower illuminance threshold up to 50% of the year across the depth of the room based on white and cream wall colour. The Double LowE glazing maintains the lower illuminance threshold for up to 40% of the year with the white and cream wall colour irrespective of orientation.

This analysis highlights the significance of the colour of the walls within a space which is particularly noticeable when the amount of light available is low. With the white and cream walls, the lower illuminance threshold is achieved for $\geq 25\%$ of the year across the depth of the room irrespective of glazing system and orientation. In comparison although the darker coloured walls achieve this lower threshold when a person is directly facing the window, when they are facing away from the window they only achieve it with the Double Glazed systems. Although it may be unlikely that the entire room would be painted the red or blue colours used in this comparison, it is common for one wall within a room to be painted with an 'accent' colour which can often be a stronger colour than the rest of the walls. This study has shown that the use of this colour would have an impact on the light reaching the eye of a person in the room.

The effect of the depth of the room is also evident across these different room scenarios. Up to a distance of approximately 4.5m from the window wall all three glazing systems provide enough light to reach the lower illuminance threshold for at least 50% of the year when a person is facing towards the window. Beyond this point there is a steep drop off across all glazing systems and to varying degrees based on the surface colour of the walls. This underlines the impact of the position of a person within the room relative to the window wall.

Overall, in Cardiff, if all wall colours are considered, a glazing system with a visible transmittance value no lower than that of the Double Glazed LowE system at 0.61 would need to be specified in order for the lower illuminance threshold to be achieved. If a glazing system with a lower transmittance than this was specified careful consideration of the other parameters would need to be taken such as the depth of the room and the colour of the walls.

Table 9.10 provides an overview of the percentage of the year, on average, that both lower and upper illuminance thresholds will be reached with each glazing system.

Table 9.10: Percentage of the year lower and upper illuminance thresholds are achieved with each glazing system in Cardiff, UK

	Double Clear Glazing		Double LowE Glazing		Triple LowE Glazing	
	Facing window	Facing away	Facing window	Facing away	Facing window	Facing away
Lower threshold: 200lux	80	40	70	25	70	25
Upper threshold: 840lux	35	0	20	0	10	0

9.3.1.2 Effect of combined parameters within the Case Study room in Helsinki, Finland

At the beginning of this section Figure 9.29 shows the percentage of the year a given illuminance level is exceeded between 6am and 5pm in Helsinki. Figure 9.28 to Figure 9.34 show that due to the reduced annual external illuminance during this period of the day in Helsinki, in comparison to Cardiff, the illuminance thresholds are reached for a smaller percentage of the year.

Double Clear glazing

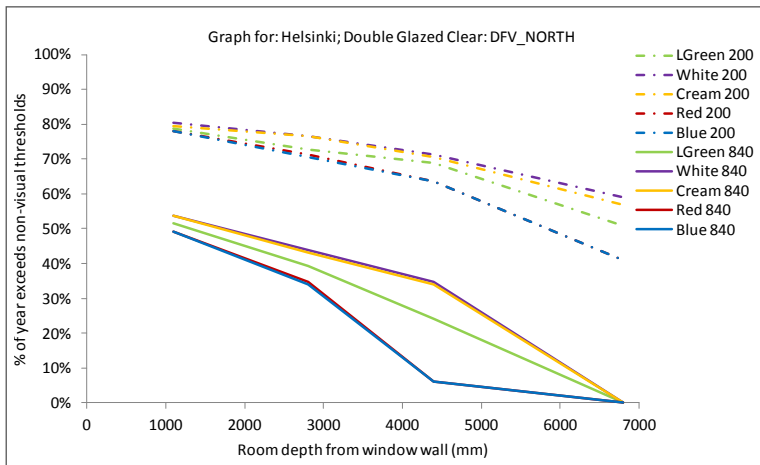


Figure 9.28: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

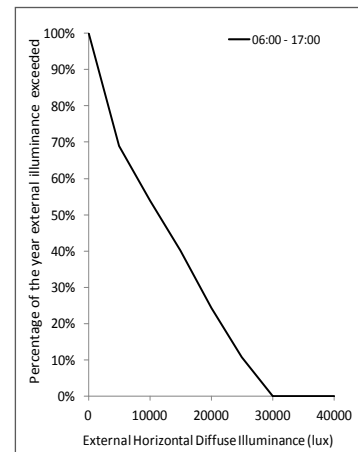


Figure 9.29: Percentage of year given horizontal diffuse illuminance exceeded between 6am-5pm in Helsinki

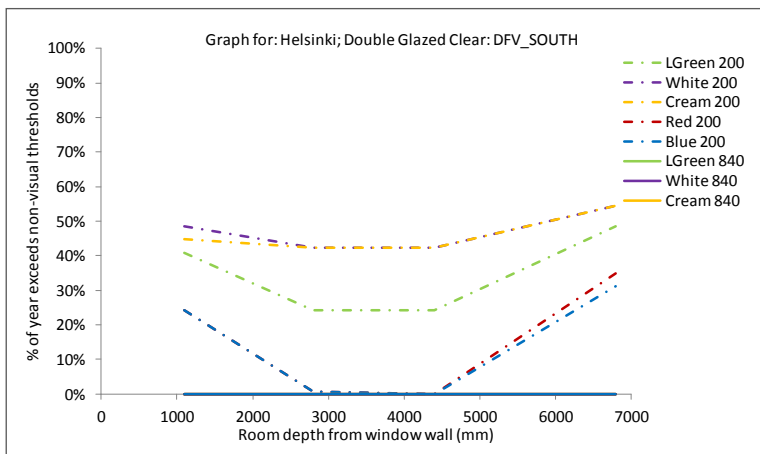


Figure 9.30: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Double Clear glazing: facing away from window

Lower illuminance threshold achieved for $\leq 50\%$ of the year with lighter colour walls. Upper threshold not met.

Figure 9.28 shows that when a person is facing the window the Double Clear glazing achieves both lower and upper illuminance thresholds, indicated by the dashed lines and solid lines respectively, across the depth of the room. The lower threshold is achieved between 40-80% across the depth of the room for all wall colours. Figure 9.30 shows that the upper illuminance threshold is not achieved for any percentage of the year when a person is facing away from the window.

Double LowE glazing

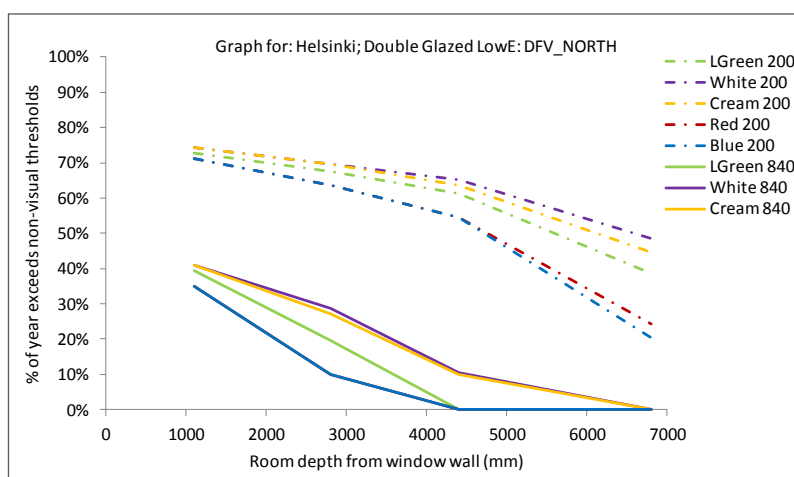


Figure 9.31: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

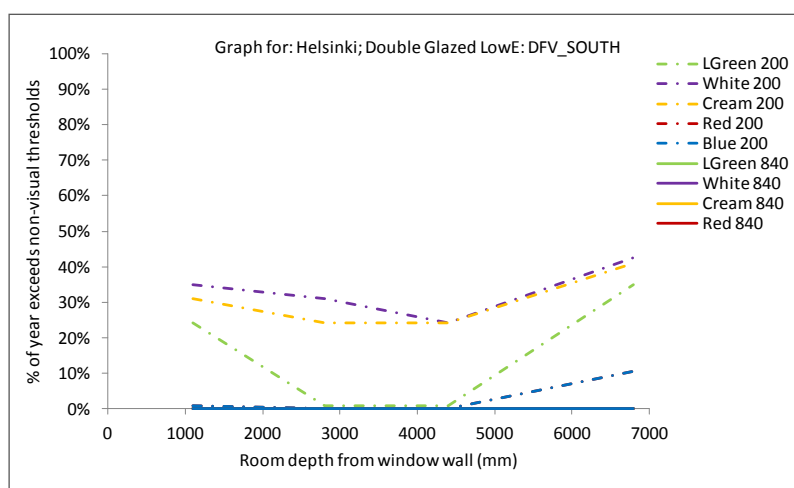


Figure 9.32: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall

Figure 9.31 shows that with the Double LowE glazing when a person is facing the window the upper threshold is achieved for a maximum of 40% of the year across the depth of the room based on all the wall colours. The dashed lines show that the lower illuminance threshold is achieved between 20-75% of the year for all wall colours. Figure 9.32 shows that, like the Double Clear glazing, the upper illuminance threshold is not achieved for any percentage of the year when a person is facing away from the window, indicated by the absence of any solid lines on the graph. Only with the lighter coloured walls is the lower illuminance threshold achieved for any significant percentage of the year.

Double LowE glazing: facing window

Lower and upper illuminance thresholds achieved up to 3m from the window wall for between 10-75% of the year based on all wall colours.

Double LowE glazing: facing away from window

Lower illuminance threshold achieved across the full depth of the room with white and cream walls, for a max. of 40% of year.

Triple LowE glazing

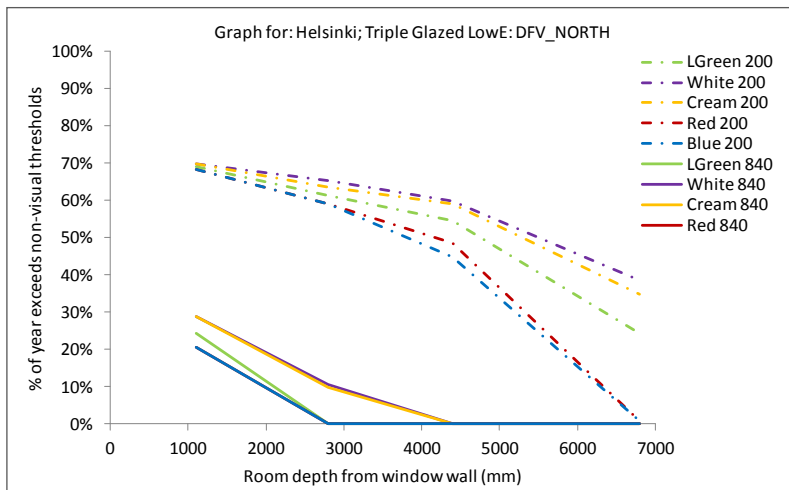


Figure 9.33: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

Triple LowE glazing: facing window

Up to 4.5m from window wall lower threshold is achieved for $\geq 45\%$ of year based on all wall colours.

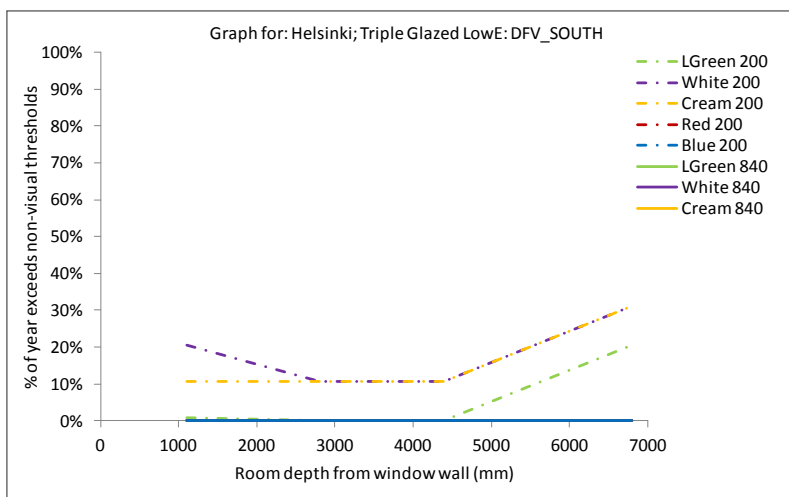


Figure 9.34: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Triple LowE glazing: facing away from window

Facing away from window only white and creams wall colours achieve lower illuminance threshold.

Figure 9.33 shows that, with Triple LowE glazing, when a person is directly facing the window the upper threshold is achieved for up to 30% of the year, this maximum value is achieved with white and cream walls at a position 1m from the window. Beyond approximately 4.5m from the window this upper threshold is no longer achieved with any of the wall colours. The lower illuminance threshold, indicated by the dashed lines, is achieved for a maximum of 70% of the year based on the range of wall colours tested. At approximately 4.5m into the room there is a steep drop off, at the furthest point within the room the lower threshold is only achieved for between 25-40% of the year based on the lighter wall colours.

Figure 9.34 shows that when a person is facing away from the window the upper illuminance threshold is not achieved for any percentage of the year. The lower threshold is only achieved with the lighter coloured walls for approximately 20% of the year, based on white and cream walls.

In summary, the study of the effect of the combined parameters based on the Case Study room in Helsinki shows that, like Cardiff, when a person is facing away from the window the upper illuminance threshold is not achieved with any of the glazing systems. When a person is facing in this direction the lower illuminance threshold is only achieved for a significant percentage of the year when the walls within the room are a light colour such as the light green, cream or white. The only exception to this is with the Double Clear glazing with which the lower illuminance threshold is also reached when the walls are painted the darker colours of blue and red, although only for an average of 15% of the year.

Similarly with Cardiff, it is clear that there is a depth within the room where the illuminance level significantly drops off. From approximately 4.5m from the window wall there is a significant reduction in the percentage of the year that the illuminance thresholds are achieved. However unlike Cardiff there is also a small but noticeable reduction from approximately 3m from the window wall that is particularly evident when looking at the upper illuminance threshold in Figure 9.28 and Figure 9.31.

Based on the available external diffuse illuminance in Helsinki if a person within this room was sat facing the window within 4.5m of the window they are likely to receive enough light to reach the lower illuminance threshold for between 40-70% of the year based on all the glazing systems and the colour of the walls. If they are further away than this from the window wall this illuminance threshold will only be achieved for a maximum of 35% of the year.

In this geographical location only the Double Clear glazing would provide the lower illuminance level for more than 50% of the year across the depth of the room, including both orientations, based on the lighter coloured walls. The Double LowE glazing achieves the lower illuminance threshold for at least 35% of the year with the white and cream walls. In this location a glazing system with a high visible transmittance value between 0.61-0.82 would need to be considered in order to achieve the necessary vertical illuminance to support non-visual processes.

Table 9.11 provides an overview of the percentage of the year, on average, that both lower and upper illuminance thresholds will be reached with each glazing system.

Table 9.11: Percentage of the year lower and upper illuminance thresholds are achieved with each glazing system in Helsinki, Finland

	Double Clear Glazing		Double LowE Glazing		Triple LowE Glazing	
	Facing window	Facing away	Facing window	Facing away	Facing window	Facing away
Lower threshold: 200lux	65	30	60	15	60	15
Upper threshold: 840lux	30	0	15	0	5	0

9.3.1.3 Effect of combined parameters within the Case study room in Tangier, Morocco

Figure 9.35 shows the percentage of the year a given illuminance level is exceeded between 6am and 5pm in Tangier. Figure 9.36 to Figure 9.41 show that the increased external diffuse illuminance during this period of the day results in the illuminance thresholds for non-visual response are reached for a greater percentage of the year.

Double Clear glazing

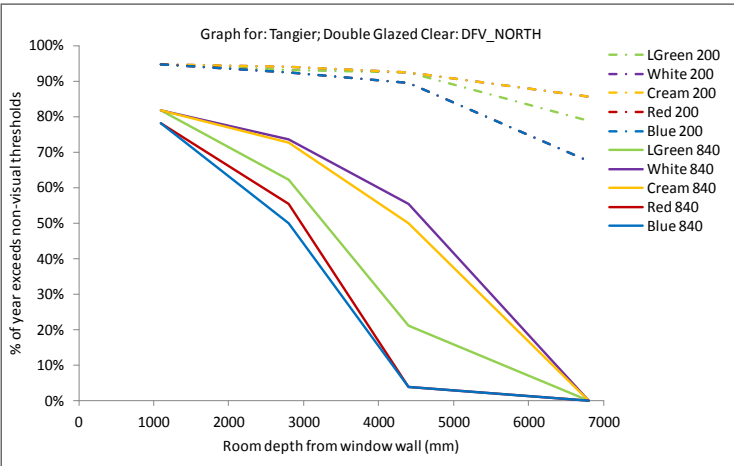


Figure 9.36: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

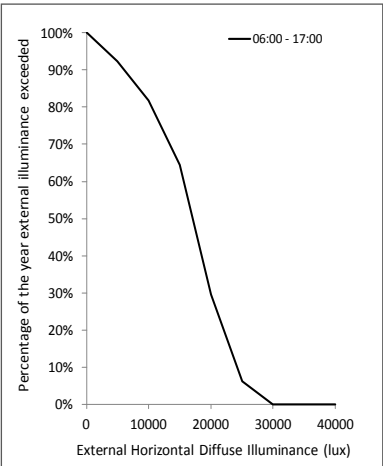


Figure 9.35: Percentage of year given horizontal diffuse illuminance exceeded between 6am-5pm in Tangier

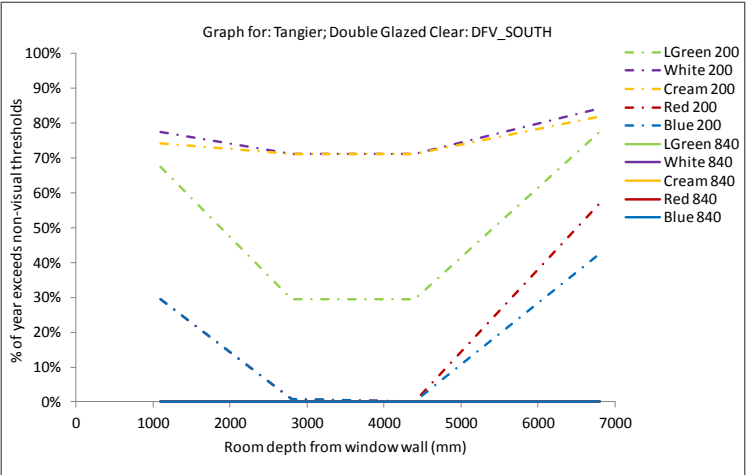


Figure 9.37: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Double Clear glazing: facing the window

Lower illuminance threshold of 200lux achieved when wall colours are light. Upper illuminance threshold not achieved at all.

Figure 9.36 shows that with the Double Clear glazing system, when a person is facing the window, the upper threshold of 840lux is reached for at least 50% of the year up to 3m into the room for all the wall colours. The lower illuminance threshold, indicated by the dashed lines, is achieved for between 70-95% of the year irrespective of wall colour. Figure 9.37 shows that the upper illuminance threshold is not achieved for any percentage of the year when a person is facing away from the window. The lower illuminance threshold is achieved for a minimum of 30% of the year with the light green walls and a minimum of 70% for the white and cream walls.

Double LowE glazing

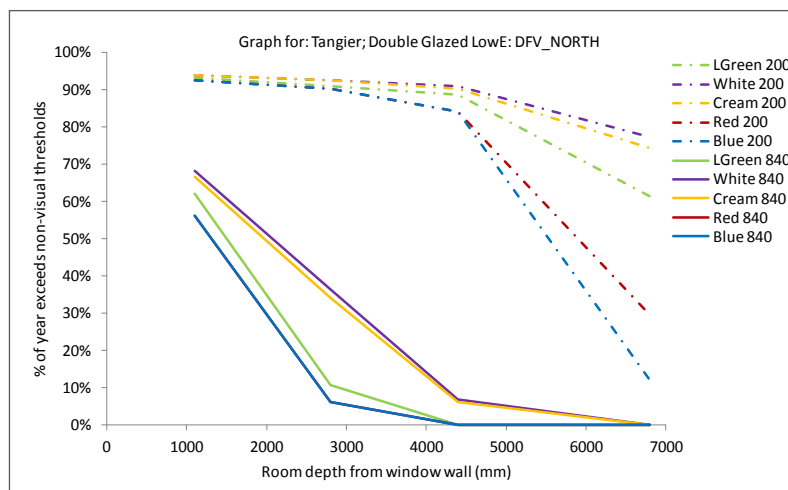


Figure 9.38: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

Double LowE glazing: facing the window

Lower illuminance threshold of 200lux achieved for 80% of the year up to 4m into the room.

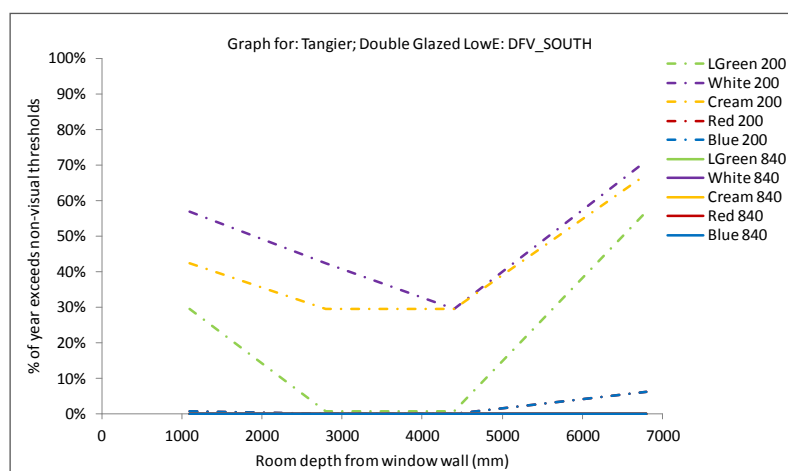


Figure 9.39: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Double LowE glazing: facing away from window

Lower illuminance threshold achieved across the depth of the room for $\geq 30\%$ of the year based on white and cream walls.

Figure 9.38 shows that when a person is facing the window the Double LowE system reaches both lower and upper illuminance thresholds up to 4.5m into the room but beyond this point there is a steep drop off. At approximately 1m from the window the 840lux threshold is achieved for 60% of the year on average but at 4.5m from the window it is only achieved for 3% on average across all the wall colours. The lower illuminance threshold, indicated by the dashed lines, is achieved across the full depth of the room between 10-95% of the year when a person is facing the window for all wall colours. Up to 4.5m into the room this lower threshold is reached for at least 85% of the year with all wall colours.

Figure 9.39 shows that the upper illuminance threshold is not achieved for any percentage of the year. The lower illuminance threshold is only achieved with the lighter wall colours and only across the full depth of the room with the white and cream walls.

Triple LowE glazing

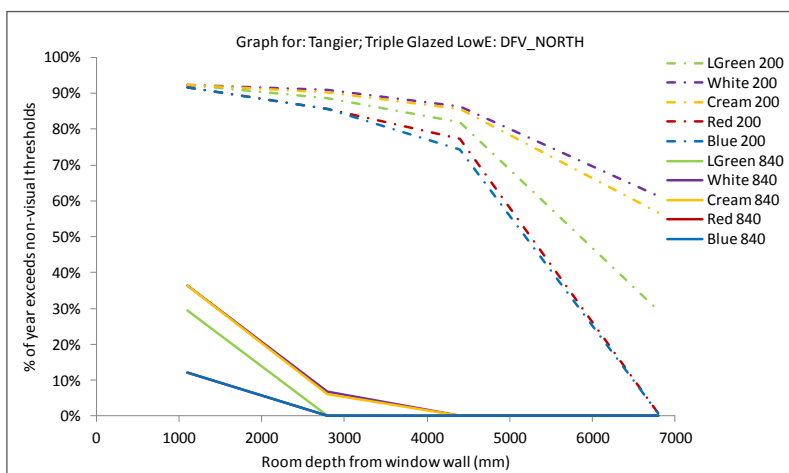


Figure 9.40: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing the window based on wall colour

Triple LowE glazing: facing the window

Up to 4m into the room lower illuminance threshold of 200lux reached for over 70% of the year.

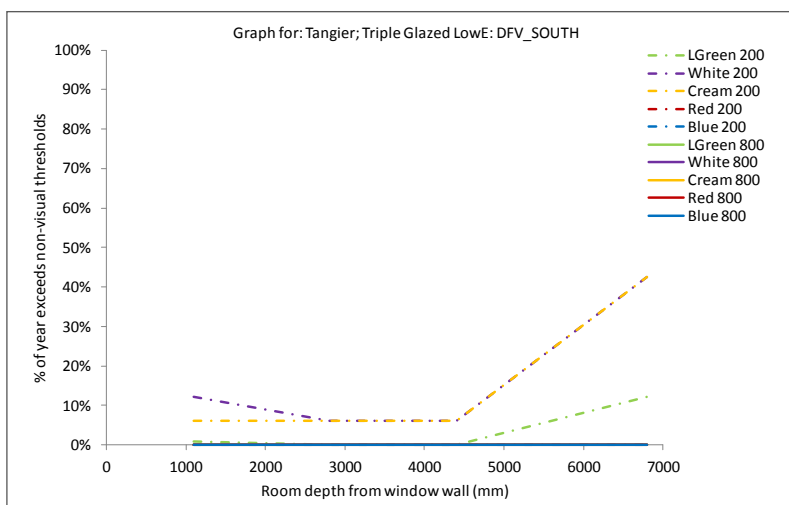


Figure 9.41: Percentage of year lower (200lux) and upper (840lux) thresholds achieved at eye, facing away from window based on wall colour

Triple LowE glazing: facing away from window

Upper illuminance threshold not reached at all when person facing away from the window.

Figure 9.40 shows that when a person is facing the window the Triple LowE glazing still achieves the lower illuminance threshold up to 4.5m into the room for between 75-85% of the year across all the wall colours. However it also shows that the upper illuminance threshold is only achieved for a maximum of 35% of the year between the window and a position approximately 3m into the room. Beyond 4.5m from the window the upper threshold is not reached at all. Figure 9.41 shows that the upper illuminance threshold is not achieved at all when a person is facing away from the window. It also shows that the lower illuminance threshold is only achieved with the white and cream walls to any significant percentage of the year.

In summary the study of the effect of the combined parameters based on the Case Study room in Tangier shows that when a person is facing the window, all three glazing systems provide enough daylight to achieve the lower illuminance threshold of 200lux for between 75-90% of the year up to 4.5m into the room, irrespective of wall colour. This is a noticeably greater percentage of the year than the other two geographical locations. However as with the other two locations when a person is facing away from the window the upper illuminance threshold is not achieved for any percentage of the year.

Looking at this worst case scenario, in terms of orientation, when a person is facing away from the window the lower illuminance threshold of 200lux is reached with all three glazing systems but only when the walls of the Case Study room are a lighter colour, with the exception of the Double Clear glazing. This is shown clearly in Figure 9.37, Figure 9.39 and Figure 9.41. This lower illuminance threshold is reached on average between 10-50% across the depth of the room based on the lighter wall colours for all three glazing systems.

Based on the available external diffuse illuminance in Tangier a person who was sat facing the window within this Case Study room within 4.5m of the window they are likely to receive enough light to reach the lower illuminance threshold for between 75-90% of the year, irrespective of the glazing system and the colour of the walls. If they are further away than this from the window wall this illuminance threshold will only be achieved between 1-70% of the year. If the person was sat facing away from the window they are likely to receive enough light to reach the lower illuminance threshold for between 5-70% of the year if they are within 4.5m of the window. If they are further than this from the window they will only receive enough light to reach this lower illuminance threshold for up to 40% of the year.

In this geographical location the specification of Triple LowE glazing would be effective to satisfy the lower illuminance threshold for a significant percentage of the year. However as this is only the case if someone is facing the window the function of the room and therefore the position of people who used it would have to be carefully considered.

Table 9.12 provides an overview of the percentage of the year, on average, that both lower and upper illuminance thresholds will be reached with each glazing system.

Table 9.12: Percentage of the year lower and upper illuminance thresholds are achieved with each glazing system in Tangier, Morocco

	Double Clear Glazing		Double LowE Glazing		Triple LowE Glazing	
	Facing window	Facing away	Facing window	Facing away	Facing window	Facing away
Lower threshold: 200lux	90	50	80	25	80	25
Upper threshold: 840lux	42	0	21	0	5	0

9.4 Summary and conclusions from Chapter 9

This Chapter has integrated all the elements affecting the availability of light at the eye, and shown how this affects the light levels within the Case Study room in three different geographic locations.

It is important to remember that there is not any consensus yet about **how long** the eye must receive light above a given threshold to entrain the circadian system or to achieve alertness. Therefore it is not possible to produce quantitative results for the effect of glazing on the human body at this stage. However, we can draw some quantitative conclusions from the work which gives some indication as to the likely acceptability of various room and glazing combinations:

- If we assume the upper threshold value of 840 lux is required to achieve alertness and circadian entrainment then NO combinations work if the occupant faces away from the window.
- The glazing type and lighter wall colours are important elements in achieving sufficient light at the eye if the lower 200 lux threshold is used, when the occupant faces away from the window
- Light colour walls are key elements to achieving sufficient daylight deeper into rooms
- When an occupant is sat facing the window then the glazing type does not have a significant effect on daylight availability – though this can lead to glare and discomfort in certain circumstances

It also appears from the study that triple glazed low E systems are unlikely to meet even the lower threshold requirements when the occupants do not face the window, assuming that a 10 – 20% achievement of threshold is not going to be enough in practical terms. A person who is sat facing away from the window would only receive enough light at their eye to stimulate the lower illuminance threshold of 200lux for a maximum of 11% of the year irrespective of the location. This Triple LowE glazing system has a visible transmittance value of 0.48; although this was the lowest of the glazing samples tested it does provide a conservative example as there are other glazing systems on the market which have lower visible transmittance values.

From the best to worst glazing systems examined within this Chapter, in terms of total visible transmittance, there is a 57% variation in light distribution based on the average vertical illuminance. The Double Glazed LowE system would achieve light distribution within the room such that both the lower and upper illuminance thresholds are reached to varying degrees based on the other parameters. Facing away from the window the lower illuminance threshold would be achieved up to a maximum of approximately 60% but only with the lighter

coloured walls of the Case Study room. The Double Glazed Clear and Double Glazed Low E samples acceptability will depend on how long the eye needs to exceed threshold levels to meet its biological needs and this is not yet known. However, the Clear Double Glazing system does show clear advantages over the Low E Double Glazing system and should be the system of choice where other constraints allow. Overall based on this work it would appear prudent to minimise the reduction of light at the window.

It should also be noted that by using the 200lux as the lower illuminance threshold provides a conservative assessment of whether these glazing systems are effective in supporting the non-visual system. This level of illuminance would stimulate subjective alertness however the proposed lower illuminance threshold for circadian phase-resetting has been assumed as 370lux which is more than 1.5 times this illuminance level. Based on the study above it is likely that some if not all of these glazing systems would struggle to achieve this higher illuminance threshold for circadian phase-resetting, particularly if a person was facing away from the window.

It is evident from this study that the depth of the room also has an impact on the amount of light that reaches the eyes of a person within the room, which reinforces research by others and guidance on lighting environments. However it may not have been anticipated that there would be a significant reduction in vertical illuminance at approximately 4.5m from the window wall, particularly as the window head height within the Case Study room is in effect at the ceiling height of 3.7m. This is a generous ceiling height and would have been anticipated to provide enough light for the full depth of this Case Study room. There was also a measurable reduction in illuminance beyond 3m from the window wall. This was also evident even when a person was facing the window and in particular with the darker wall colours.

As was discussed in Chapter 8, the orientation or the direction of view of a person within the room has a significant effect on the light that is received at their eyes. This has been shown to amount to 80% variation between the best case scenario, directly facing the window and the worst case scenario facing away from it. If a person is facing away from the window in this case study room they would not receive enough light at their eye to reach the proposed upper illuminance threshold of 840lux for non-visual response irrespective of location or glazing specification.

In summary, it seems unlikely that many tasks undertaken in rooms will involve all the occupants facing the windows – with most preferring to sit at an angle to the window to

minimise glare on work surfaces. It therefore seems reasonable to conclude that the choice of glazing system will have a marked and quantifiable effect on the light achieved at the eye in many operational room scenarios, and therefore the eyes ability to provide the necessary light information for biological regulatory functions. Further work at an hourly level would be worth undertaking once greater certainty over the length of time the eye needs to be exposed to light levels above the thresholds is achieved.

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Chapter 10

Conclusions

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The main aim of the thesis was to establish whether the choice of glazing system could be impacting on the well-being of the building occupant based on the daylight they receive within a building interior. The thesis therefore focused on the role of daylight beyond supporting the visual system, and the impact of glazing on the daylight that is received by the eye when a person is within a building. As has been shown by the case study there are a number of parameters within the design of interior space that have an impact on daylight distribution, so it was also necessary to establish the relative importance of the choice of glazing in respect to these other parameters.

This focused the thesis outcomes on two main questions:

- Does glazing impact on the non-visual processes connected to the eye?
- What is the relative importance of glazing in the overall room design on these non-visual processes?

In answer to these questions the thesis has shown that the choice or specification of glazing system within a building envelope does have an important impact on the non-visual processes connected to the eye. Of the variables within the control of the designer of a room the specification of the glazing has been shown to have the most significant impact on the daylight received at the eye.

So what are the implications of these findings to the architectural industry?

This thesis has re-emphasized the role of daylight within architectural design, showing that it has a much greater significance to humans than just being a source of light. It has also shown that there appears to be a clinically proven link between health and the quality of daylight provided in buildings.

This thesis suggests that the drivers for design development need to be reconsidered to now prioritize daylight levels above energy efficiency and ultimate energy saving. In practice it would appear from the studies undertaken that clear double glazing is the best compromise and could provide the minimum light transmission standard for many locations and buildings. It turn it might also mean larger areas of glazing within the building envelope particularly if the use of multilayered glazing systems is maintained.

This thesis has shown that glazing specification is directly connected to the light received at the eye of a building occupant and will ultimately have an impact on their well-being. It has also shown that there are a number of other design parameters such as colour and reflectance

of surfaces that have an impact on the light that is received by a building occupant. The case study particularly emphasizes the importance of choice of surface colour, highlighting it as having a similar impact to the choice of glazing specification. As this thesis identified that the spectral quality of light plays a significant role in stimulating the non-visual system, it suggests that the choice of colour for internal finishes should also have higher priority in the design and operation of buildings.

The thesis findings raise the question of how to choose the most appropriate and beneficial glazing system to support non-visual processes. The thesis has shown that there is not a singular answer to this question. The appropriate choice of glazing is dependent on a number of variables including the geographical location of the building, the colours of the room finishes, the orientation of the room within the building as well as the activity or function of the room and therefore the orientation of a person within the room. This is a broad spectrum of variables and future work will look to analyse the degree to which they are interconnected and establish their specific levels of influence on the non-visual processes of the building user.

The study on glazing systems showed that those glazing systems with multiple layers especially those incorporating coatings for low emissivity and solar control had the most significant impact on the total visible transmittance. The implication of this effect is that the proposed illuminance thresholds for supporting non-visual processes are not achieved at the eye of the occupant in many circumstances. This is particularly the case in the more northerly Northern Hemisphere locations such as Finland and Norway where daylight availability is significantly reduced throughout certain parts of the year. For Northern hemisphere locations the use of clear double glazed systems would seem to be the best compromise between providing daylight and reducing energy consumption.

Future work will need to address this conflict between maximising daylight penetration within building interiors and the drive to reduce energy consumption and CO₂ emissions in buildings. The thesis suggests that building performance criteria fixated on energy efficiency will potentially come at the detriment of occupant wellbeing. By readdressing the priorities of building performance to emphasise the importance of daylight it is likely that the focus of energy efficiency could shift away from just the thermal performance of the building envelope to a more holistic view of the role of the building envelope on the overall health and well-being of the occupants.

Advances in material technology have meant that glass coatings can be manufactured to interact with specific parts of the spectrum in different ways. An example of this is electrochromic glazing, the transmittance properties of which changes depending on the available external illuminance often giving the glass a blue tint (Mardaljevic, Painter, & Waskett, 2014). Future work will need to establish the effect of this type of glass on the perception of the occupant as well as the non-visual requirements of the body as this has not been conclusively proven.

This thesis has brought together multiple areas of research to establish a new area of focus on the implications of the specification of a single building component. This has potentially significant ramifications for the design of future buildings.

Based on this conclusion the thesis has also highlighted that the system of photometry used within buildings currently only captures the human visual response to light stimuli. The lighting guidance for designers as well as the equipment used to measure light levels are based entirely around the response of the human visual system. As the findings from the biomedical community become clearer as to the specific lighting requirements of the human non-visual system then this guidance will need to evolve to produce lighting environments that support the non-visual system as well. In particular a better understanding of the duration of light stimulus needed above a given threshold to support various non-visual processes will provide the means to further quantify the effect of glazing specification. Further research is needed within operational buildings on the wider impact of daylight on the non-visual processes in humans.

The case study also highlighted that there is a significant difference between the measurement of light on a horizontal plane and the light received on a vertical plane at the same position within a room. This showed that it is not enough to rely solely on horizontal illuminance measurements to ascertain whether a given space will provide enough light to support the non-visual system, and further emphasizes the need for the development of a new system of measurement for light levels within the built environment.

In conclusion, this thesis has shown that the light requirements of the human body are complex and that our understanding of its needs is still evolving. For the specific situation of the design and specification of the built environment this thesis has demonstrated that, based on current understanding of the non-visual lighting requirements of the eye, the impact of the

choice of glazing system is significant and requires further design guidance to be produced to help avoid the worst impacts of poor glazing choice.

Future work in this area requires interdisciplinary studies to examine the impact of the various parameters noted here on a host of issues. These range from quantifiable impacts on the human body, such as melatonin suppression, through to psychological studies on mood, depression and other impacts arising from the provision of daylight. A debate is also needed on the trade-off between energy efficiency and the impact of daylight provision on human well-being, as it is clear that there is a tension between these two design drivers that will need to be resolved.

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Appendix A

Glass and Glazing Sample Database

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Optical Data for all glass and glazing extracted from WINDOW6

Glazing type	Sample no.	Sample descriptor	Glass ID	Product description	Tsol	Tvis	Rfvis	Rbvis	Avis	SHGC	LSG
Reference											
	1	Clear_A_3	102	CLEAR_3.DAT	0.83	0.90	0.1	0.1	0.1	0.9	1.0
	2	Clear_B_4	1608	Clear_4.CSG	0.85	0.90	0.1	0.1	0.1	0.9	1.0
	3	Clear_C_6	9804	Clear6.LOF	0.77	0.88	0.1	0.1	0.1	0.9	1.0
	4	Clear_C_8	9805	Clear8.LOF	0.73	0.87	0.1	0.1	0.1	0.9	1.0
	5	Clear_B_8	1603	Clear_8.CSG	0.78	0.89	0.1	0.1	0.1	0.9	1.0
	6	Bronze_A_3	100	BRONZE_3.DAT	0.65	0.68	0.1	0.1	0.1	0.9	0.8
	7	Grey_A_3	104	GRAY_3.DAT	0.61	0.62	0.1	0.1	0.1	0.9	0.7
	8	Clear_A_6	103	CLEAR_6.DAT	0.77	0.88	0.1	0.1	0.1	0.9	1.0
	9	Bronze_A_6	101	BRONZE_6.DAT	0.49	0.53	0.1	0.1	0.1	0.8	0.6
	10	Blue_A_6	11070	HANLITE SKY BLUE 6mm.SGG	0.44	0.58	0.1	0.1	0.1	0.8	0.7
	11	Green_A_6	11014	PARSOL H-GREEN 6mm.SGG	0.47	0.74	0.1	0.1	0.1	0.8	0.9
	12	UltraClear_A_6	5004	STRPH_6.PPG	0.89	0.91	0.1	0.1	0.1	0.9	1.0
	13	UltraClear_B_6	9571	Low Iron_6.CAG	0.90	0.92	0.1	0.1	0.1	0.9	1.0
Window films on single clear glass											
	14		2751	RE15SIARXL.mmm	0.12	0.17	0.6	0.6	0.6	0.3	0.5
	15		1546	SLCLGY06.SWT	0.19	0.36	0.1	0.1	0.1	0.7	0.5
Coated glass											
	16	LowE	4142	Kglass6mm.NSG	0.67	0.81	0.1	0.1	0.1	0.8	1.0
	17	LowE	11394	PLANITHERM ONE 6mm.SGG	0.45	0.77	0.2	0.2	0.2	0.5	1.5
	18	Reflective Solar	9911	EclAdvGrey6.LOF	0.29	0.32	0.3	0.1	0.1	0.7	0.5
	19	Solar	3236	CG7138C6.grd	0.39	0.77	0.0	0.0	0.0	0.6	1.2
	20		3124	SGNU61C6.grd	0.40	0.67	0.2	0.1	0.1	0.6	1.1
LowE											
	21	LowE_A	3457	GrdTEX62C6.grd	0.26	0.69	0.1	0.0	0.0	0.5	1.3
	22	LowE_B	2157	LoE336-6.CIG	0.27	0.70	0.1	0.0	0.0	0.6	1.3
	23	LowE_C	1654	CED14-46_6.CSG	0.29	0.48	0.2	0.1	0.1	0.6	0.8
	24	LowE_D	11394	PLANITHERM ONE 6mm.SGG	0.45	0.77	0.2	0.2	0.2	0.5	1.5
LowE - Dble											
	25	LowE_A + clear	3457 + 103	GrdTEX62C6.grd+CLEAR_6.DAT	0.23	0.61	0.1	0.1	0.1	0.2	2.6
	26	LowE_B + clear	2157 + 103	LoE336-6.CIG+CLEAR_6.DAT	0.23	0.62	0.1	0.1	0.1	0.2	2.6
	27	LowE_C + clear	1654 + 103	CED14-46_6.CSG+CLEAR_6.DAT	0.24	0.43	0.2	0.2	0.2	0.3	1.7
	28	Clear + LowE_D	103 + 11394	CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG	0.38	0.69	0.2	0.2	0.2	0.4	1.7

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Double glazing - low-E										
29		103+4142	CLEAR_6.DAT+Kglass6mm.NSG		0.53	0.73	0.2	0.2	0.6	1.2
30		103+11394	CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG		0.38	0.69	0.2	0.2	0.4	1.7
31		4118+4142	OptifloatClear6mm+Kglass6mm.NSG		0.54	0.73	0.2	0.2	0.6	1.2
32		2157+103	LoE366+CLEAR_6.DAT		0.23	0.62	0.1	0.1	0.2	2.6
33		2157+2162	LoE366+189-6.CIG		0.23	0.61	0.1	0.1	0.2	2.5
Solar Control										
34	Solar Control A	2047	LoE240-6.CIG (Cardinal)		0.22	0.42	0.1	0.0	0.6	0.7
35	Solar Control B	11025	SGG COOL-LITE KNT164 6mm		0.45	0.65	0.0	0.1	0.7	0.9
36	Solar Control C	3124	SGNU61C6.grd		0.40	0.67	0.2	0.1	0.6	1.1
37	Solar Control D	9909	EclAdvClr6.LOF		0.58	0.67	0.3	0.3	0.7	0.9
38	Solar Control E	9935	SolarE6.LOF		0.44	0.60	0.1	0.1	0.8	0.8
39	Solar Control A + clear	2047+103	LoE240-6.CIG (Cardinal)+CLEAR_6.DAT		0.19	0.37	0.1	0.1	0.2	1.9
40	Solar Control B + clear	11025+103	SGG COOL-LITE KNT164 6mm+CLEAR_6.DAT		0.36	0.57	0.1	0.1	0.4	1.5
41	Solar Control C + clear	3124+103	SGNU61C6.grd+CLEAR_6.DAT		0.33	0.60	0.2	0.1	0.4	1.7
42	Solar Control D + clear	9909+103	EclAdvClr6.LOF+CLEAR_6.DAT		0.46	0.60	0.3	0.3	0.5	1.2
43	Solar Control E + clear	9935+103	SolarE6.LOF+CLEAR_6.DAT		0.35	0.53	0.1	0.2	0.4	1.4
44	Solar Control C On Green	3125+103	SGNU61C6.grd+CLEAR_6.DAT		0.22	0.51	0.2	0.1	0.2	2.2
45	Solar Control D on Green	9910+103	EclAdvEvGrn6.LOF+CLEAR_6.DAT		0.20	0.43	0.2	0.3	0.2	2.1
46	Solar Control E On Green	9954+103	SolarEEvGrn6.LOF+CLEAR_6.DAT		0.17	0.40	0.1	0.1	0.2	2.2
47	SpectralSolar_A	11049+103	COOL-LITE KS 147 + CLEAR.DAT		0.23	0.43	0.4	0.4	0.2	1.7
48	SpectralSolar_B	11197+103	COOL-LITE SKN 174 + CLEAR.DAT		0.32	0.67	0.1	0.1	0.3	2.0
49	SpectralSolar_C	3138+103	SGSR20C6.grd + CLEAR.DAT		0.12	0.18	0.3	0.3	0.1	1.4
50	SpectralSolar_D	103+3413	CLEAR.DAT + SNX6227C6.grd		0.23	0.61	0.1	0.1	0.3	1.8
51	SpectralSolar_D1	3039+3413	Gray_6.grd+SNX6227C6.grd		0.12	0.31	0.1	0.1	0.2	1.7
52	SpectralSolar_E	9909+103	EclAdvClr6.LOF+ CLEAR.DAT		0.46	0.60	0.3	0.3	0.5	1.2
53	SpectralSolar_E1	9911+103	EclAdvGrey6.LOF+ CLEAR.DAT		0.23	0.29	0.1	0.3	0.3	1.1
Double glazing - specific solar control										
54		3124+103	SGNU61C6.grd+clear_6.DAT		0.33	0.60	0.2	0.1	0.4	1.7
55		11025+103	COOL-LITE KNT164 6mm.SGG+CLEAR_6.DAT		0.36	0.57	0.1	0.1	0.4	1.5
56		11025+11465	COOL-LITE KNT164 6mm.SGG+PLANITHERM TOTAL +6mm.SGG		0.34	0.57	0.1	0.1	0.4	1.5
57		2047+103	LoE240-6.CIG+103		0.19	0.37	0.1	0.1	0.2	1.9
58		9935+103	SolarE6.LOF+CLEAR_6.DAT		0.35	0.53	0.1	0.2	0.4	1.4
Laminates and laminated glazing										
59	Laminate Clear	3370	CG5527Emb23L3.grd		0.2	0.59	0.1	0.1	0.5	1.2

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Body tinted glass											
60	Bronze B 6	9721	6. Bronze.VRD			0.48	0.49	0.1	0.1	0.8	0.6
61	Grey A 6	9894	SUPGRV6.LOF			0.08	0.09	0.04	0.04	0.8	0.1
62	DkGrey 5	11080	PARSOL DARK GREY 5mm.SGG			0.27	0.14	0.04	0.04	0.8	0.2
63	Grey C 6	9834	GREY6.LOF			0.41	0.44	0.1	0.1	0.8	0.5
64	Grey C 8	9835	GREY8.LOF			0.31	0.33	0.05	0.05	0.8	0.4
65	Green B 6	9844	GREEN6.lof			0.46	0.76	0.1	0.1	0.8	0.9
66	Bronze C 6	9854	BRONZE6.LOF			0.48	0.51	0.1	0.1	0.8	0.6
67	Bronze C 8	9855	BRONZE8.LOF			0.39	0.44	0.1	0.1	0.8	0.5
68	UltraClear C 6	9814	Optiw6.lof			0.89	0.91	0.1	0.1	0.9	1.0
69	EmGreen A 6	4107	EmeraldGreen6mm.NSG			0.25	0.51	0.1	0.1	0.8	0.7
70	ArtBlue A 6	4101	ArticBlue6mm.NSG			0.35	0.54	0.1	0.1	0.8	0.7
71	ArtBlue B 6	9864	ARCB16.LOF			0.33	0.53	0.1	0.1	0.8	0.7
72	ArtBlue B 8	9865	ARCB18.LOF			0.25	0.42	0.1	0.1	0.8	0.5
73	Clear D 6	9804	CLEAR6.LOF			0.77	0.88	0.1	0.1	0.9	1.0
74	Clear D 8	9805	CLEAR8.LOF			0.73	0.87	0.1	0.1	0.9	1.0
Double glazing - tinted											
75	Grey + Clear	9911+103	EclAdvGrey6.LOF+CLEAR 6.DAT			0.23	0.29	0.3	0.2	0.2	1.1
76	Blue + LowE	4101+4142	ArticBlue6mm.NSG+Kglass6mm.NSG			0.25	0.44	0.1	0.1	0.3	1.6
77	Blue + Clear	4101+103	ArticBlue6mm.NSG+CLEAR 6.DAT			0.28	0.48	0.08	0.1	0.3	1.6
78	Grey + Clear	9834+103	GREY6.LOF+CLEAR 6.DAT			0.32	0.39	0.07	0.12	0.3	1.12
79	Bronze +Clear	9721+103	6. Bronze.VRD+CLEAR 6.DAT			0.37	0.43	0.08	0.1	0.4	1.1
80	Bronze +LowE	9721+4142	6. Bronze.VRD+Kglass6mm.NSG			0.32	0.40	0.1	0.1	0.4	1.1
81	Green + Clear	4107+103	EmeraldGreen6mm.NSG+CLEAR 6.DAT			0.22	0.46	0.1	0.1	0.2	2.0
82	Green + LowE	4107+4142	EmeraldGreen6mm.NSG+Kglass6mm.NSG			0.19	0.42	0.1	0.1	0.2	2.0
Coated tinted glass											
83	Blue	9950	SolarEArB16.lof			0.20	0.36	0.1	0.1	0.7	0.5
84	Bronze	9908	EclAdvBrnz6.LOF			0.35	0.38	0.3	0.1	0.7	0.6
85	Green	3129	SGNU50G6.grd			0.23	0.47	0.1	0.0	0.8	0.6
86		11281	COOL-LITE ST 467 6mm			0.31	0.54	0.2	0.1	0.7	0.7
Double glazing											
87		103+103	CLEAR 6.DAT+CLEAR 6.DAT			0.61	0.79	0.1	0.1	0.7	1.2
88		102+102	CLEAR 3.DAT+CLEAR 3.DAT			0.70	0.81	0.1	0.1	0.7	1.1
89		102+102	CLEAR 3.DAT+CLEAR 3.DAT			0.70	0.81	0.1	0.1	0.7	1.1
90		103+103	CLEAR 6.DAT+CLEAR 6.DAT			0.61	0.79	0.1	0.1	0.7	1.2
Triple glazing - clear											
91		103	CLEAR 6.DAT+CLEAR 6.DAT+CLEAR 6.DAT			0.49	0.70	0.2	0.2	0.6	1.2
92		103	CLEAR 6.DAT+CLEAR 6.DAT+CLEAR 6.DAT			0.49	0.70	0.2	0.2	0.6	1.2

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Triple glazing - solar control									
93		9935+4118+4142 SolarE6.LOF+OptifloatClear6mm.NSG+Kglass6mm.NSG	0.26	0.44	0.2	0.2	0.3	1.4	
94		9935+4118+103 SolarE6.LOF+OptifloatClear6mm.NSG+CLEAR_6.DAT	0.29	0.48	0.1	0.2	0.3	1.4	
95		9935+103+103 SolarE6.LOF+CLEAR_6.DAT+CLEAR_6.DAT	0.29	0.48	0.1	0.2	0.3	1.4	
Triple glazing - low-E									
96		103+11394 CLEAR_6.DAT+CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG	0.32	0.62	0.3	0.3	0.4	1.6	
97		4118+4142 OptifloatClear6mm+OptifloatClear6mm+Kglass6mm.NSG	0.44	0.65	0.2	0.2	0.5	1.2	
98		3124+103+11394 SGNU61CG+CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG	0.22	0.48	0.3	0.3	0.3	1.8	
99		2157+103+103 LoE366+CLEAR_6.DAT+CLEAR_6.DAT	0.20	0.56	0.1	0.2	0.2	2.5	
100		2157+103+2162 LoE366+CLEAR_6.DAT+89-6.CG	0.20	0.55	0.1	0.2	0.2	2.5	
Triple glazing - tinted									
101		4101+103 ArcticBlue6mm.NSG+CLEAR_6.DAT+CLEAR_6.DAT	0.24	0.43	0.1	0.2	0.3	1.6	
102		4101+4118+4142 ArcticBlue6mm+OptifloatClear6mm+Kglass6mm.NSG	0.21	0.40	0.1	0.2	0.2	1.6	
103		4101+103+4142 ArcticBlue6mm+CLEAR_6.DAT+Kglass6mm.NSG	0.21	0.40	0.1	0.2	0.2	1.6	
104		9721+103+103 6.Bronze.VRD+CLEAR_6.DAT+CLEAR_6.DAT	0.30	0.39	0.1	0.2	0.4	1.1	
105		9721+103+4142 6.Bronze.VRD+CLEAR_6.DAT+Kglass6mm.NSG	0.25	0.36	0.1	0.2	0.3	1.1	
106		4107+103 EmeraldGreen6mm+CLEAR_6.DAT+CLEAR_6.DAT	0.18	0.41	0.1	0.2	0.2	2.0	
107		9834+103 GREY6.LOF+CLEAR_6.DAT+CLEAR_6.DAT	0.26	0.35	0.1	0.2	0.3	1.1	
Quadruple glazing - clear									
108		103+103+103+10 CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT	0.40	0.63	0.2	0.2	0.5	1.2	
109		103+103+103+10 CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT	0.40	0.63	0.2	0.2	0.5	1.2	
110		102+102+102+10 CLEAR_3.DAT+CLEAR_3.DAT+CLEAR_3.DAT	0.51	0.68	0.3	0.3	0.6	1.1	
Quadruple glazing - low-E									
111		103+103+103+41 CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT+Kglass6mm.NSG	0.35	0.59	0.3	0.2	0.5	1.2	
112		103+103+103+11 CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT+PLANITHERM ONE 6mm.	0.27	0.56	0.3	0.3	0.4	1.5	
Quadruple glazing - tinted									
113		4101+103+103+41 ArcticBlue6mm+CLEAR_6.DAT+CLEAR_6.DAT+Kglass6mm.NSG	0.17	0.36	0.1	0.2	0.2	1.6	
114		9721+103+103+1 6.Bronze.VRD+CLEAR_6.DAT+CLEAR_6.DAT+CLEAR_6.DAT	0.24	0.35	0.1	0.2	0.3	1.1	
115		9721+103+103+4 6.Bronze.VRD+CLEAR_6.DAT+CLEAR_6.DAT+Kglass6mm.NSG	0.21	0.32	0.1	0.2	0.3	1.1	
Combined systems									
116	Dble_Combined_A	9909+4142 EclAdv + Kglass	0.41	0.56	0.3	0.3	0.5	1.2	
117	Dble_Combined_A1	9910+4142 EclAdv+Grn6 + Kglass	0.18	0.40	0.2	0.3	0.2	2.0	
118	Dble_Combined_B	11034+11465 COOL-LITE ST 120 + PLANITHERM TOTAL+	0.11	0.18	0.3	0.3	0.1	1.4	
119	Dble_Combined_B1	11043+11465 COOL-LITE STB 120 + PLANITHERM TOTAL+	0.12	0.19	0.3	0.2	0.1	1.3	
120	Dble_Combined_C1	11409+11465 COOL-LITE KNT 164 + PLANITHERM TOTAL+	0.34	0.57	0.1	0.1	0.4	1.5	
121	Dble_Combined_C1	11456+11465 COOL-LITE KNT 464 H + PLANITHERM TOTAL+	0.21	0.47	0.1	0.1	0.2	2.1	
122	Triple_Combined_A	3124+103+11394 SGNU61CG+CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG	0.22	0.48	0.3	0.3	0.3	1.8	
123	Triple_Combined_A1	3125+103+11394 SGNU61G6+CLEAR_6.DAT+PLANITHERM ONE 6mm.SGG	0.16	0.40	0.2	0.3	0.2	2.2	
124	Triple_Combined_B	9935+103+4142 SolarE6.LOF+CLEAR_6.DAT+Kglass6mm.NSG	0.26	0.44	0.1	0.2	0.3	1.4	

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Appendix B

Validation of the process used by the *SATELLIGHT* programme

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This appendix will provide a brief overview of research supporting the validation of the Satellites programme and the accuracy of the data provided by the European Database of Daylight and Solar Radiation.

Evaluations of the Heliosat method using Meteosat images have been undertaken for a number of specific locations using ground measured data for the *SATELLIGHT* programme (Skartveit & Olseth, 2000). One study by Skartveit & Olseth looking at ground measurements taken over two years (1996/97) in Bergen, Norway shows what is considered to be a negligible mean-bias-deviation between the two sets of global irradiance data of $2\text{-}3\text{Wm}^{-2}$ which for solar elevations above 15° amounts to less than 1% of global irradiance. The root-mean-bias-deviation was shown to range from 22% to 38% for solar elevations $>30^\circ$ and $<15^\circ$ respectively.

A general observation was made that the Heliosat values tended to overestimate global irradiances for overcast conditions and underestimate for clear sky conditions in comparison to the ground measurements. This evaluation was also carried out for diffuse irradiance values and this deviation was found to grow further. Mean-bias deviation for Heliosat estimations of diffuse irradiation were approximately 5-10% of the ground measurements of average global irradiance and the root-mean-bias-deviations being 2.6-2.9 times greater than this.

To validate the methods adopted, the *SATELLIGHT* programme used 25 test sites across Europe taking two different approaches to establish the level of precision of the data; firstly by comparing half hourly estimates from the satellite to ground measurements and secondly by assessing end user products generated from the satellite to those generated from ground measurements such as cumulative frequency curves. The comparison with ground measurements is the most relevant in this instance. The results of the evaluation suggest that under clear or partly clear conditions there is a good correlation between the measured and modelled data but that there is greater deviation under overcast conditions.

The overall assessment of all sky conditions on an annual basis showed that there was a mean-bias-deviation (MBD) ranging from -1% to 3% and a root-mean-bias-deviation (RMBD) ranging from 20% to 40% (20% in Southern Europe due to the high frequency of clear and sunny days, 40% in Northern Europe where there is a high frequency of cloudy days). Although the RMBDs are high this is explained by the *SATELLIGHT* team by the fact that they are comparing 30min values and that the deviation would be smaller if monthly or daily values were being compared.

The *SATELLIGHT* project also references a study undertaken by Perez et al (1997) which compared the accuracy of site specific hourly irradiances derived from satellite images to those obtained from extrapolation of ground measurement stations in close proximity to each other. The results showed that for hourly data derived from the satellite become more accurate than a ground station if the distance away from the measurement station exceeds 34km. This suggests that data provided by *SATELLIGHT* offers equal if not greater accuracy for locations outside a 34km radius of a ground measurement station.

Appendix C

Total transmittance analysis based on geographical location

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This appendix will look at the effect of the specification of the glazing system on the light that reaches the inner surface of the glass, based on the available external illuminance of two geographical locations; Paris and Tangier as a continuation of the analysis in Chapter 7. This will give an initial understanding of its ability to provide adequate light intensity at the correct time of day for the stimulation of non-visual processes.

Effect of average annual external illuminance in Paris, France

The difference between external illuminance levels during the summer and winter is less pronounced at the more southerly latitude of Paris, France than in a location such as Helsinki but there is still a notable difference as would be expected. In June the global horizontal illuminance values get up above 10,000lux between 7-8am and do not drop below again until between 8-9pm. The position of the sun in the sky during the summer months means that the greatest illuminance levels are at the horizontal plane whereas during the winter months with the sun in a lower position within the sky the south facing facade receives the highest illuminance levels. It is also evident from the two graphs in Figure 1 that the global illuminance levels for south facing surfaces do not vary as greatly as all the other surfaces due to the contribution of the direct solar beam.

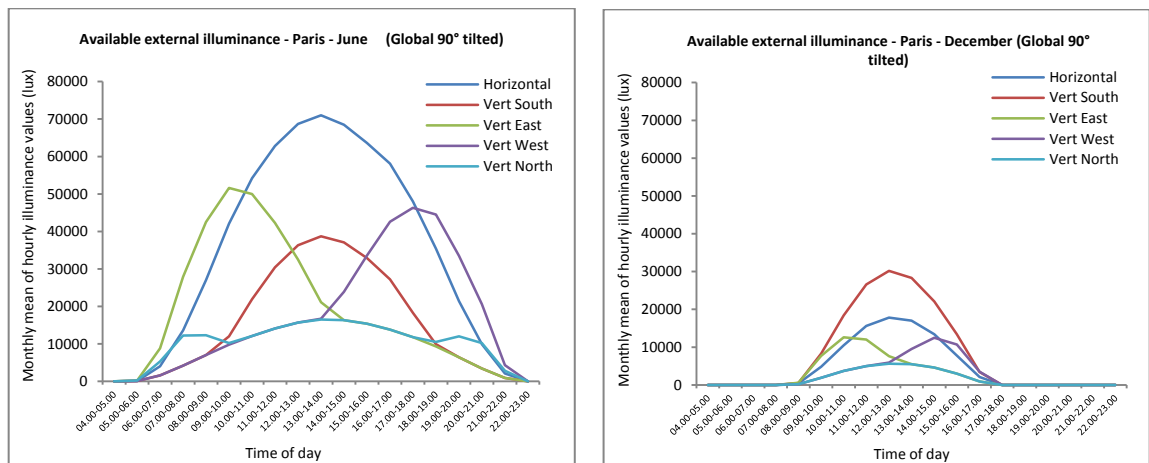


Figure 1: Graphs showing average external global illuminance values for horizontal and vertical surfaces in Paris during winter and summer months extrapolated from climate data from SATELLIGHT

When looking at the diffuse illuminance values shown in Figure 2, the difference between the vertical planes are not as pronounced due to the exclusion of direct solar beam. It highlights that during the summer months there is less difference between the four orientations of vertical surface as they are each receiving a more equal amount of light from the sky vault due to the position of the sun. The difference across the day is dependent on the position of the

sun in the sky as this will have an effect on the brightness of that part of the sky. Excluding the south facing vertical plane, during the winter months the diffuse vertical illuminance does not reach much above 7500lux with the north facing vertical surface having a peak of around 5000lux in the middle of the day. During the summer months the vertical illuminance reaches around 20,000lux in each orientation except for the north facing vertical plane.

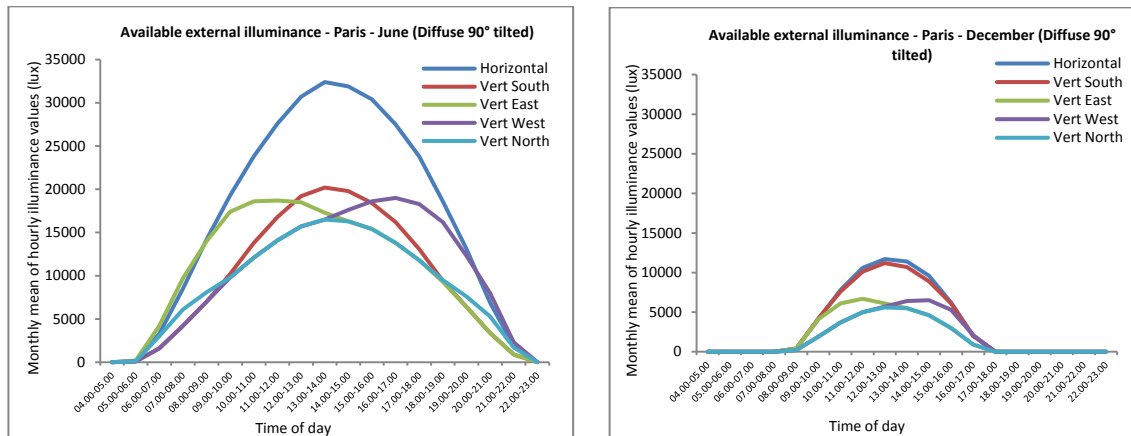


Figure 2: Graphs showing available external diffuse illuminance for Paris during winter and summer months extrapolated from climate data from *SATELLIGHT*

Based on the average global external illuminance for an east facing vertical plane during December, the graph in Figure 3 shows the total transmittance of six glazing types. It gives a picture as to the illuminance levels that might be expected on the internal face of the glazing system. The difference between maximum transmittance across an average day for Double Glazed LowE system and Triple Glazed Bronze tinted systems is approximately 2500lux with the peak for the triple bronze tinted glazing system being around 4200lux. In comparison with Helsinki it is evident initially that the daily average period of daylight is longer in Paris with peak illuminance levels being noticeably higher. The triple glazed systems provide over 4000lux at their peak which was not achieved even by the Double Glazed LowE system when simulated for Helsinki.

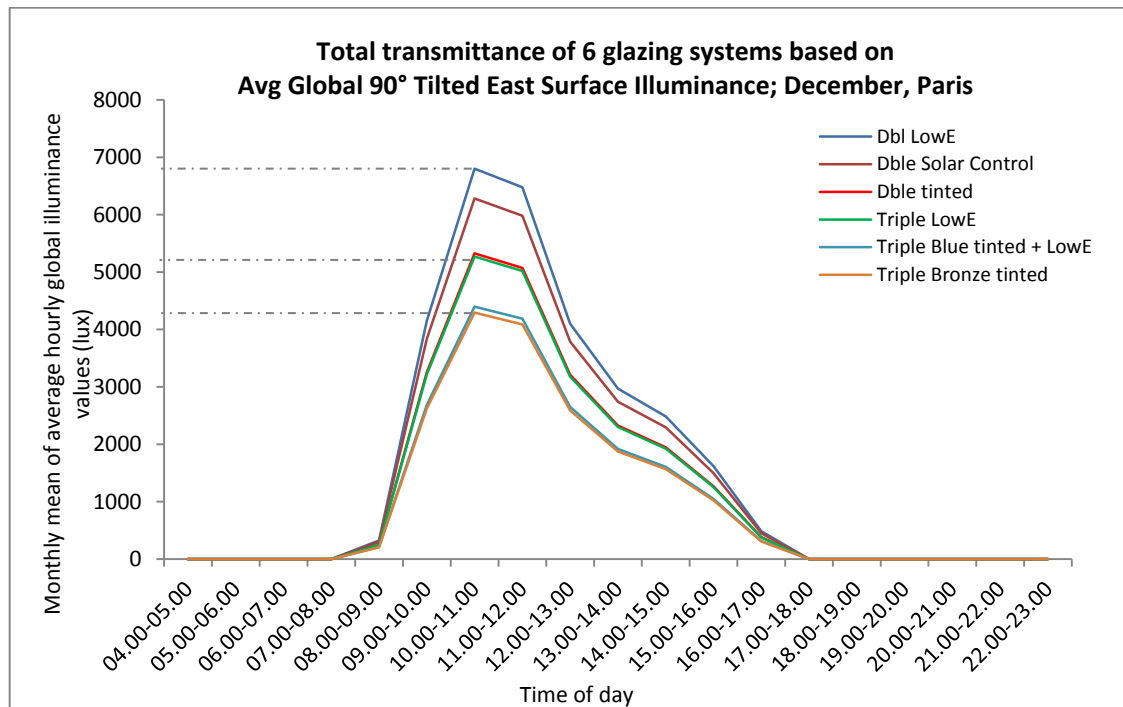


Figure 3: Total transmittance of 6 glazing systems based on average global vertical illuminance at an East facing vertical plane during December in Paris based on data extrapolated from *SATELLIGHT*

In the summer months the position of the sun in the sky means that the illuminance levels remain higher across the day and the hours of daylight are extended. This in turn means that the illuminance levels during the early morning hours, highlighted as significant for entrainment of the circadian system are high enough to achieve the stimulation threshold. This can be seen by the illuminance levels on both the north and the south facing vertical planes shown in Figure 4. However the peak illuminance levels are significantly different for these two opposing vertical planes with the south facing plane receiving greater levels of direct solar beam than the north. This high illuminance levels received by the south facing vertical plane means that total transmittance of the triple bronze tinted glazing unit reaches approximately 13,000lux during the middle of the day. This is in comparison to 5000lux on the north facing vertical plane.

Taking this into consideration in terms of the glazing systems specified it might mean that different systems should be proposed for different facade orientations. More typically this would be addressed by utilising solar shading devices on the south facing facades. However when looking at the diffuse illuminance levels the total transmittance values there is less of a difference between the North and South facades, in particular during the four hour period in the morning suggested as most potent to circadian phase resetting. The greatest difference is

with the peak illuminance levels when the Sun still has an impact on the diffuse illuminance values on the south facing vertical surfaces.

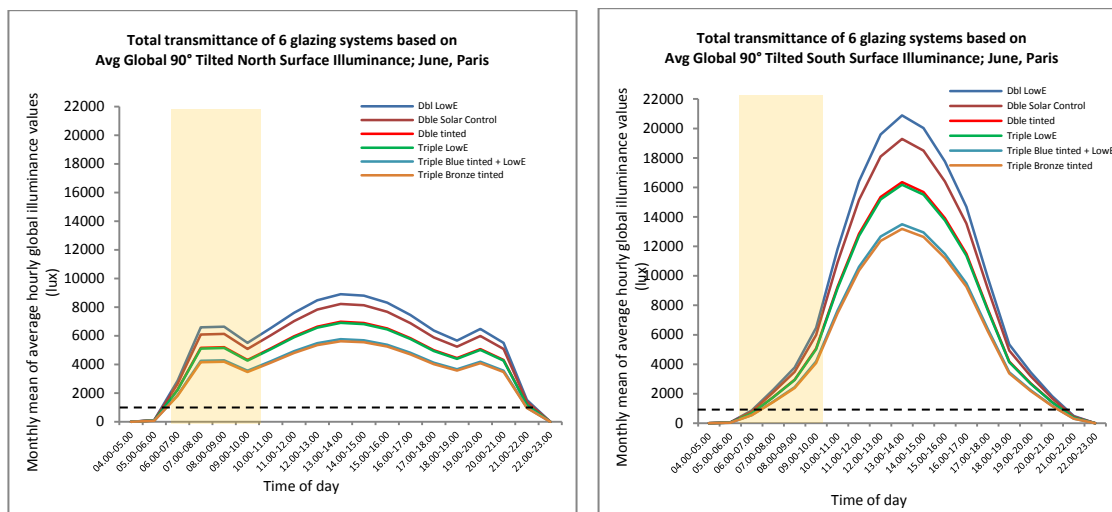


Figure 4: Comparison of total transmittance of 6 glazing systems based on external global illuminance for a North facing and a South facing vertical plane in June in Paris showing the periods of day most effective for circadian phase-resetting; 6-10am.

Clear skies and therefore contribution to illuminance levels from direct solar beam cannot be relied upon due to the changing microclimate particularly in Northern European cities such as Paris. Therefore it is important to look at the diffuse illuminance levels which could be considered a worst case scenario in terms of external illuminance levels. Overcast skies tend to produce reduced illuminance levels due to a reduced amount of high intensity solar beam, although this is not the case 100% of the time. As shown by Figure 4 the diffuse illuminance levels across an average day in June do not reach the same peak as they might with the direct solar beam contribution but still remain high enough that all transmittance values for the range of glazing types achieve the stimulation threshold. As mentioned above during the specific period in the morning there is not a significant difference between the two vertical surfaces. This might suggest that if different glazing systems were specified for the North and South facing facades this might have a detrimental effect on the light transmitted to the corresponding internal spaces.

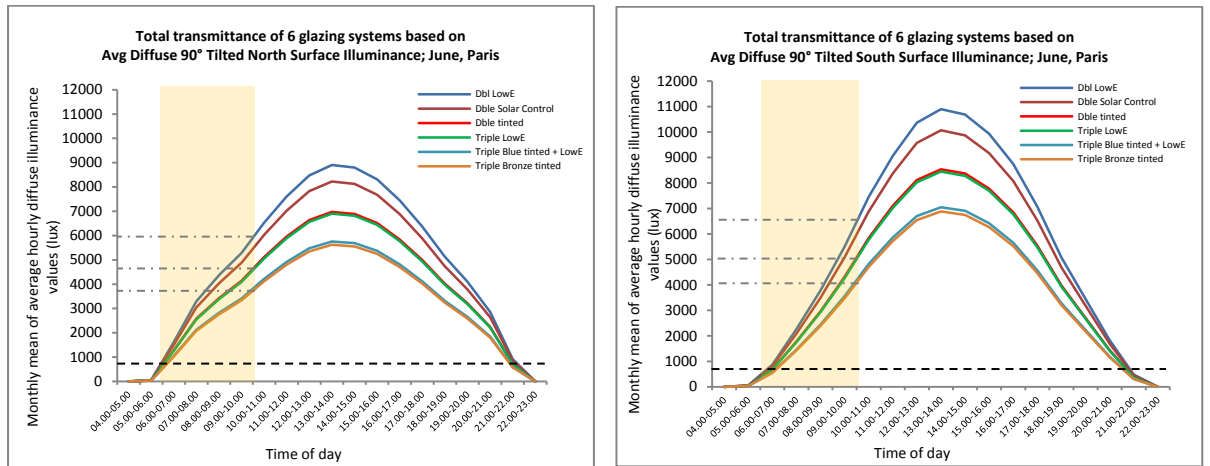


Figure 5: Comparison of total transmittance of 6 glazing systems based on external diffuse illuminance for a North facing and a South facing vertical plane in June in Paris showing the periods of day most effective for circadian phase-resetting; 6-10am.

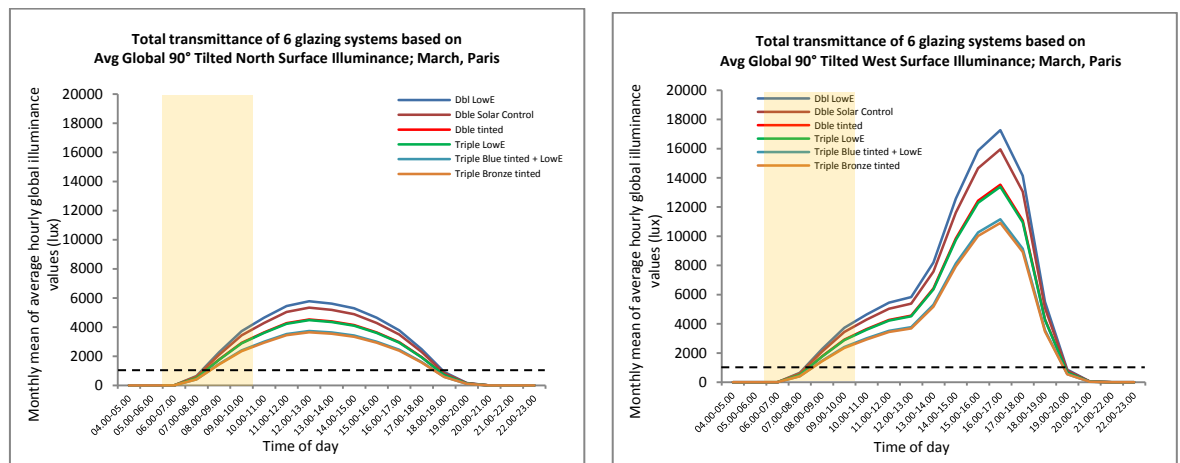


Figure 6: Comparison of total transmittance of 6 glazing systems based on external global illuminance for a North facing and a South facing vertical plane in March in Paris showing the periods of day most effective for circadian phase-resetting; 6-10am.

In spring, although the illuminance levels are reduced in comparison to the summer months the vertical illuminance levels appear to reach the necessary thresholds during the early hours of the morning for all orientations. As the sun rises later during these months the illuminance levels do not reach this necessary threshold until later in the morning around 8:00am which slightly reduces the period of time a building occupant might be exposed to the necessary light stimulus. When looking at the North and West facades at this time of day there is little difference between the global and diffuse illuminance levels. The position of the sun means that vertical planes in these orientations are not exposed to significant amounts of direct solar beam.

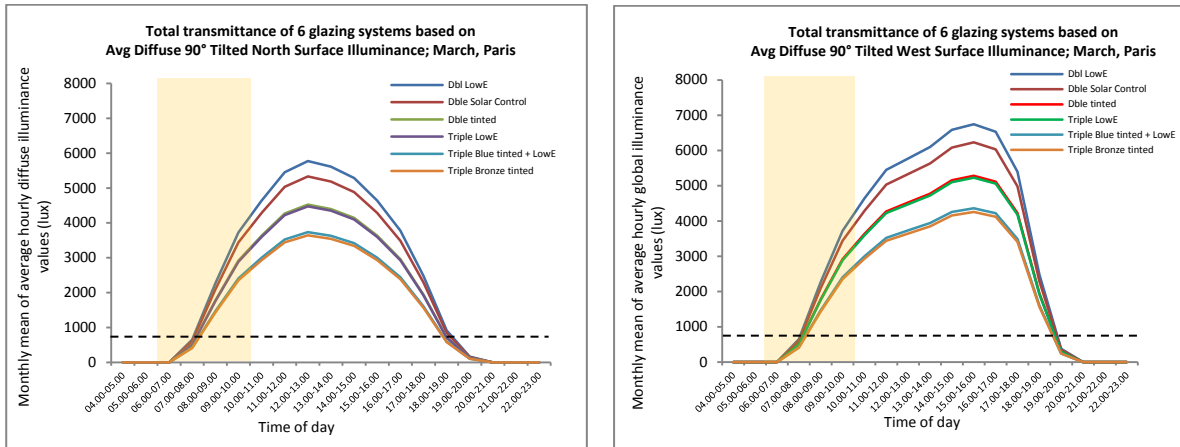


Figure 7: Comparison of total transmittance of 6 glazing systems based on external diffuse illuminance for a North facing and a South facing vertical plane in March in Paris showing the period of day most effective for circadian phase-resetting; 6-10am.

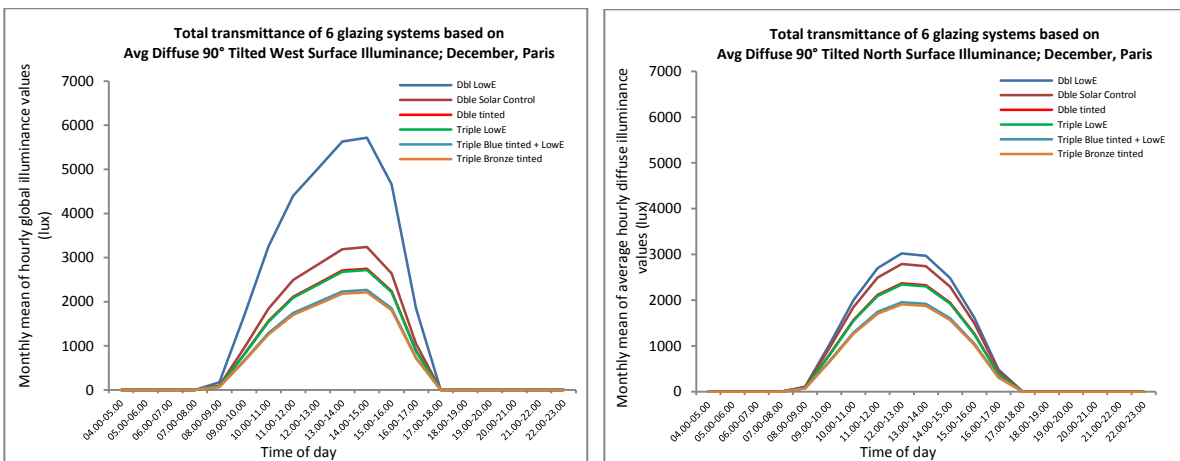


Figure 8: Comparison of total transmittance of 6 glazing systems based on external diffuse illuminance for a West facing and a North facing vertical plane in December in Paris showing the period of day most effective for circadian phase-resetting; 6-10am.

Effect of average annual external illuminance in Tangier, Morocco

At latitude of 60°10N, external illuminance levels in Tangier are consistently higher throughout the year than other two locations summarised above. Even in March the diffuse external illuminance levels shown in Figure 9 are the same as those of Paris in June shown in Figure 2 excluding the horizontal illuminance values. When compared to the global illuminance values for the same month it is evident the impact that the direct solar component has at this latitude and time of year, almost quadrupling the peak illuminance values.

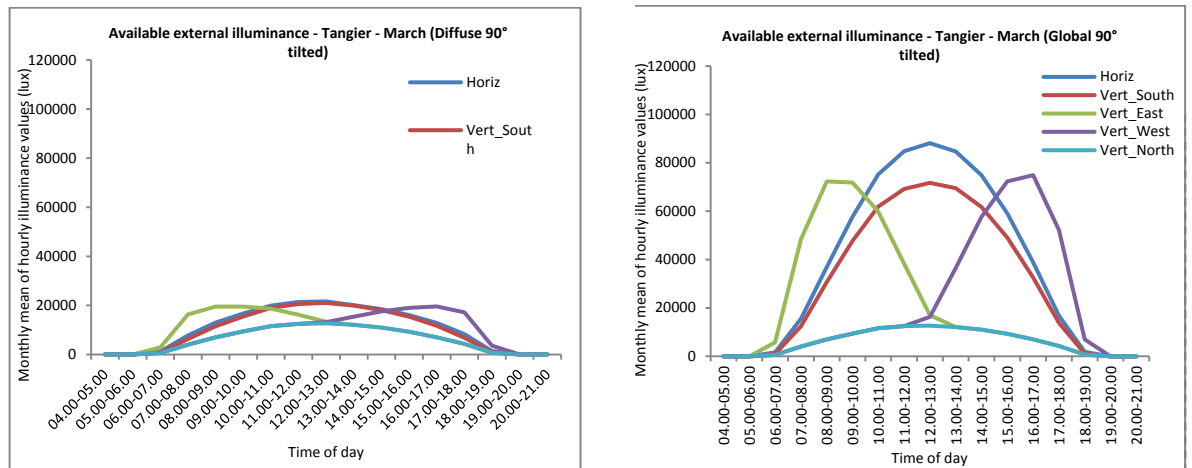


Figure 9: Graphs showing available external global and diffuse illuminance for Tangier during an average day in March based on data extrapolated from *SATELLIGHT*

The difference between the diffuse illuminance values for March and December is not that significant in terms of peak illuminance levels with the form of the graphs appearing quite similar, but there is a reduced difference between the four orientations. The length of daylight hours is also shorter with the sun rising later and setting earlier. In terms of the requirements of the non-visual system this might have an impact on the available illuminance levels at the earlier part of the day needed for resetting circadian phase.

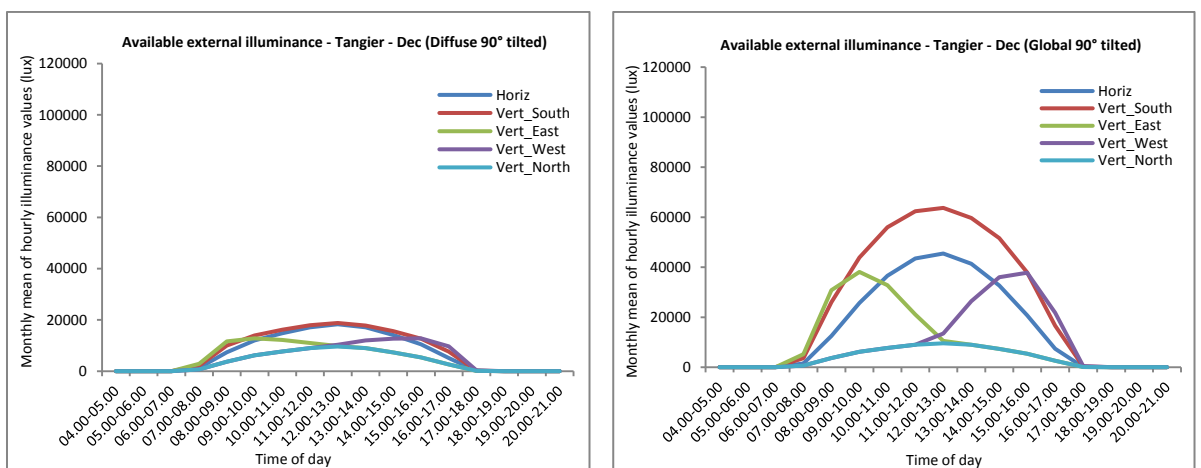


Figure 10: Graphs showing available external global and diffuse illuminance for Tangier during December based on data extrapolated from *SATELLIGHT*

On initial analysis the illuminance values on the north facing vertical plane remain fairly consistent throughout the year, not significantly affected by the contribution of the direct solar beam. When looking at the north facing vertical plane separately throughout the year it shows that there is approximately a 7000lux difference between the diffuse illuminance values for

June and December. The diffuse illuminance values for this north facing vertical plane do not go much above 15,000lux throughout the year, depending on the transmittance values of the glazing used on a facade with this orientation it may not provide enough daylight to the internal spaces. The diffuse illuminance values are greater for the West facing vertical surface but they only reach 20,000lux towards the latter part of the day influenced by the position of the sun in the sky. The average illuminance levels are also quite similar for March, June and September.

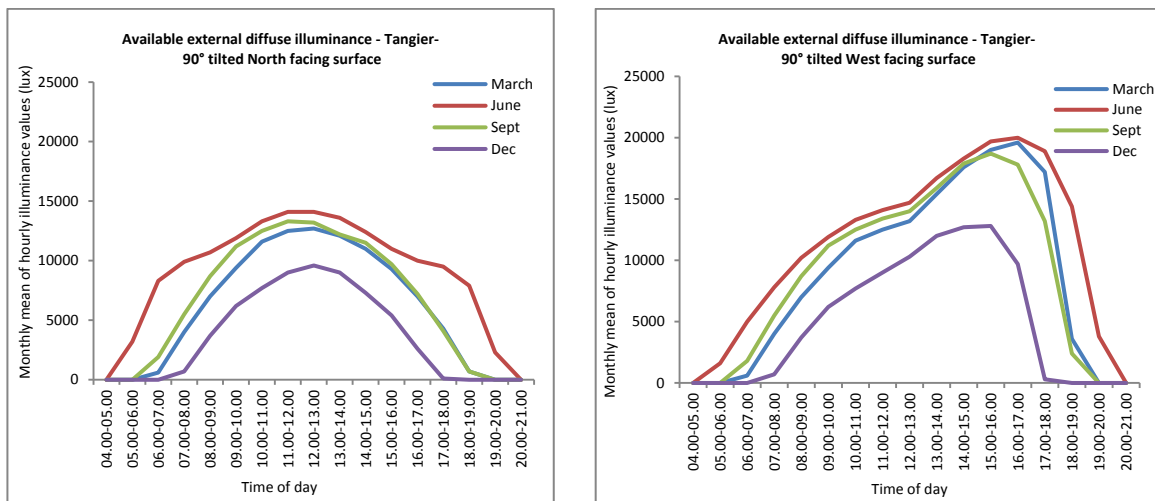


Figure 11: Comparison of external diffuse illuminance on two orientations of vertical plane across an average year in Tangier based on data extrapolated from *SATELLIGHT*

By then adding in the range of glazing types it is possible to see the effect on the illuminance levels which might be anticipated at the inner surface of the glazing system. This is shown for two vertical planes with different orientations in Figure 12. The orange section highlights the period of the day that has been identified as the most effective for circadian phase-resetting between 6:00-10:00am in the morning. By also identifying the approximate threshold line it is possible to see that all of these glazing systems transmit enough visible light to stimulate the human circadian system although only half way through the recommended period of time.

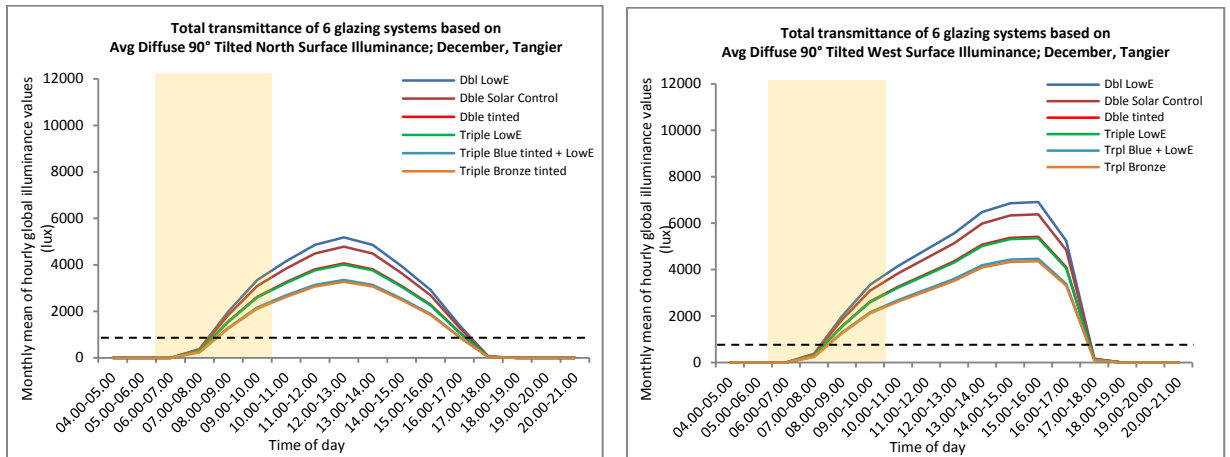


Figure 12: Comparison of total transmittance of 6 glazing systems based on external diffuse illuminance for a North facing and a South facing vertical plane in December in Tangier showing the period of day most effective for circadian phase-resetting; 6-10am.

If we look at the average global illuminance during the month of December for a north facing vertical surface in closer detail as in Figure 13 it is possible to see that it is not until around 8:00am that the illuminance levels reach the lower threshold. These figures include the direct solar component, although this does not seem to greatly increase the illuminance values for a north facing surface. During this period of 4 hours in the morning the illuminance levels provided by the type 1 glazing (Double LowE) provides approximately 2800lux whereas the type 6 glazing (Triple bronze tinted) provides approximately 1800lux to the building interior. It is important to emphasise that this can only be considered as the inner surface of the glazing system but it gives a picture as to the potential availability of daylight these glazing systems provide.

December would be considered as the worst case scenario in terms of the availability of external illuminance. Figure 13 shows that there although it might be assumed that illuminance levels are consistently high at a location such as Tangier there are periods of the year when the diffuse illuminance levels would not be high enough to provide enough light internally to stimulate non-visual responses.

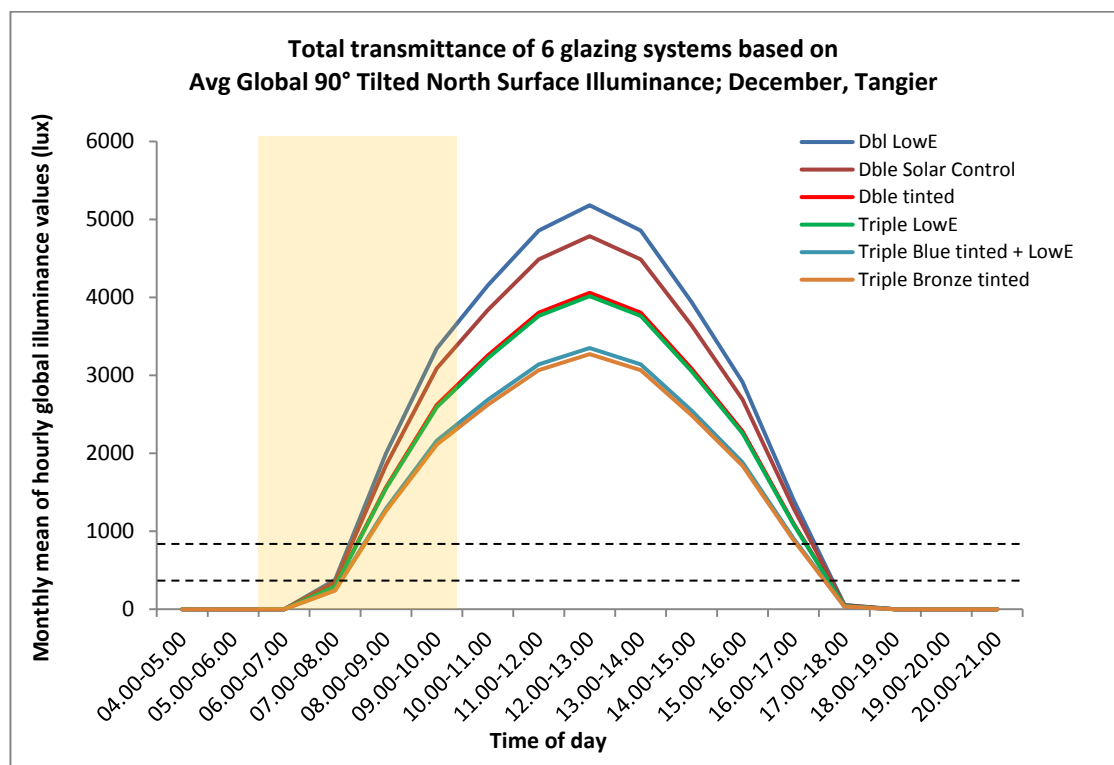


Figure 13: Comparison of total transmittance of 6 glazing systems based on external global illuminance for a North facing vertical plane in December in Tangier showing the period of day most effective for circadian phase-resetting; 6-10am.

Comparing these illuminance values for the winter months represented by the month of December with that provided during the spring, it is evident that there is a noticeable difference. However, as is shown in Figure 11 with the exception of the winter months there is a similar external illuminance level across the rest of the year. This is considered to be due to latitude of Tangier nearer to the equator than Paris or Helsinki.

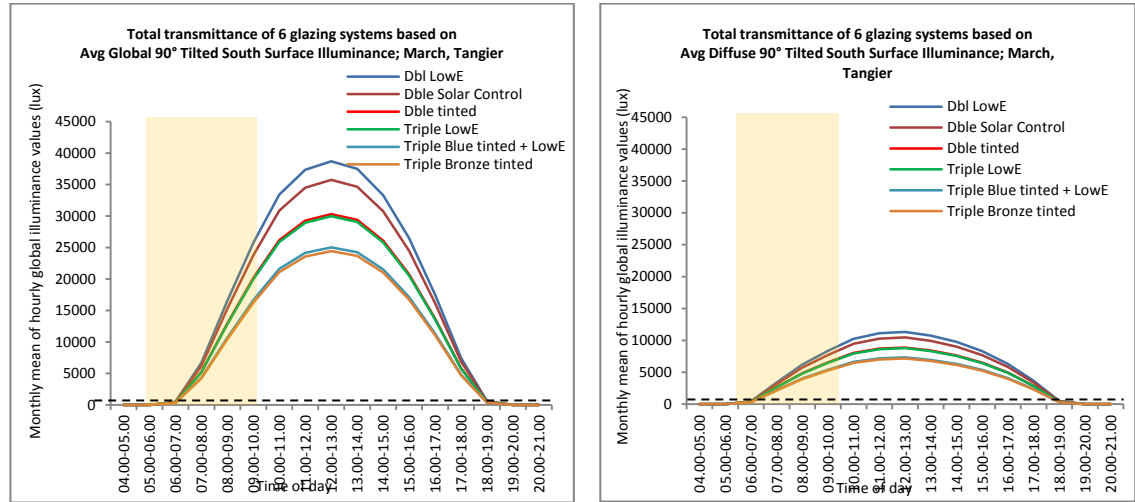


Figure 14: Comparison of total transmittance of 6 glazing systems based on external diffuse and global illuminance for a South facing vertical plane in March in Tangier showing the period of day most effective for circadian phase-resetting; 6-10am.

Based on the diffuse illuminance values, the Triple Glazed systems only achieve an illuminance level between 5000-10,000lux across an average day at the internal face of the glazing system. In comparison the global illuminance levels for this period of the year are significantly higher, particularly when considering the south facing facade.

For a location such as Tangier, there are a greater percentage of clear days across an average year therefore there will typically be a greater contribution from the direct component within the daylight available. It is likely in this location that the actual external illuminance level will be higher enough across an average year to provide enough light within a building interior with the potential exception of periods within the winter months. However it should be noted that this initial evaluation only considered the light level achieved at the inner face of the glazing system. This evaluation does not consider the effect of the room on light distribution and the impact this would have on the light received at the eye of a person in the room.

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Appendix D

Calibration of light metering equipment

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This appendix provides more detail on the physical measurements taken within the Case Study room as well as briefly outlining the process of calibration of the light meters used. The Minolta CL-200A Chromo meter used was a new piece of equipment which had recently been calibrated in the factory.

The measurements at each position within the room were taken simultaneously with three photometers; one externally on the vertical plane, internally on the horizontal plane and at the chosen eye position (90° or 45° from horizontal). The photometer used to take the light level readings at the assumed eye position was a Minolta CL-200A Chromo meter and all other light meters used were calibrated to this light meter. The graphs below show the correlation between readings from each internal light meter in comparison to CL-200A and the necessary adjustment factors indicated by the trendline equation. This was used to adjust the measurements taken by the light meter #2 and #3 in order that they were aligned to the measurements taken with the Minolta CL-200A.

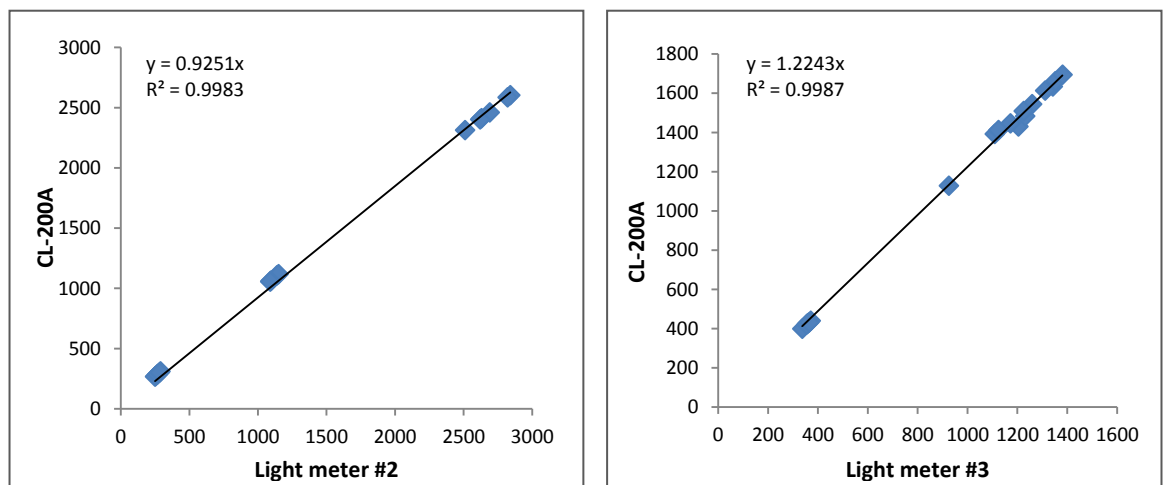


Figure 1: Calibration of light meters

External horizontal illuminance measurements were taken from an illuminance meter installed on the roof of the building, with a solar ring to prevent direct solar beam from affecting the readings. This lux meter was also calibrated against the CL-200A to ensure an accurate comparison of data. The illuminance readings taken on the roof of the building were recorded by a data logger every 30 seconds and averaged over a 5 minute period, this information was collated on a computer housed within the building.



Figure 3: External illuminance meter on the roof of the university building

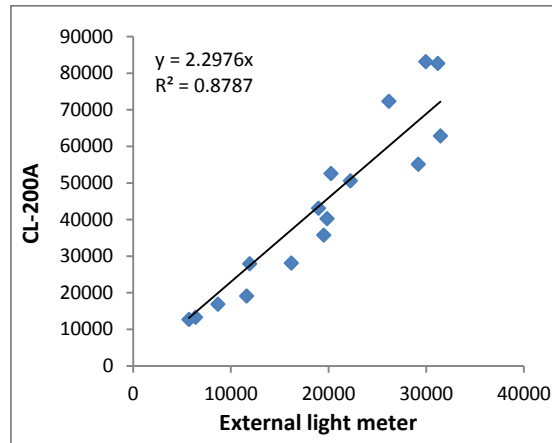


Figure 2: Calibration of external light meter

It was not possible to undertake longitudinal light level measurements within the room for a full year to provide a continuous data set which would establish at which times of the year the building occupant received enough light stimuli. Therefore it was necessary to use the physical measurements to establish both horizontal and vertical Daylight Factor values achieved across the room. This would establish the light distribution across the room and the impact on the amount of light that would reach the eye of the occupant of a range of variables such as, different positions within the room, as well as the different orientations.

By establishing the Daylight Factor values across the room in its existing state it would be possible to compare this with the computer generated model by calibrating it to the physical measurements. It would then be possible to assess the effect of changing the glazing specification on the light distribution within the virtual model, which was not possible with the actual Case Study room.

Appendix E

Further analysis of effect of angle of gaze on light reaching the eye of the
occupant within the Case Study room

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Leading on from the finding that the direction of view is important in determining the amount of light that reaches the eye, the Case Study now goes on to consider the angle of gaze. In a large percentage of scenarios it would be difficult to predict the exact position of a person's head or specifically their angle of gaze throughout the day, so this work aims to understand the range of likely light levels to be achieved to establish the boundary parameters to the problem. For this Case Study, which is in a learning environment, the room layout is based on a traditional pedagogic model where majority of the people within the room will be facing towards the teaching wall. In this arrangement it is also quite likely that the people inhabiting the room would spend a percentage of their time looking down towards the desk at a visual task, changing their angle of gaze.



Figure E.1: Diagram showing 90 + 45 degree measurement positions

From the comparison of Vertical Daylight Factor with Horizontal Daylight Factor it is clear this change of angle will have an impact on the light that is received by their eyes, something that is also considered in research of education environments by others (Bellia, Pedace, & Barbato, 2013). To assess the impact of this change in angle of gaze, a series of light measurements were also taken at 45° from vertical, angled towards the horizontal desk surface. This simulates the potential position of a person's head when looking down at a visual task on the desk and is described graphically in Figure

E.1. Calculating the DF values for a 45° inclined plane in the same four locations within the room through the four orientations enables a comparison to be made with the DF_V and DF_H values, which will clarify the effect of the angle of the head/eye position on daylight received.

This appendix will look in more depth at the impact of this angle of gaze on the light received at the eye across all measurement points within the room in comparison to the Horizontal and Vertical Daylight Factor values.

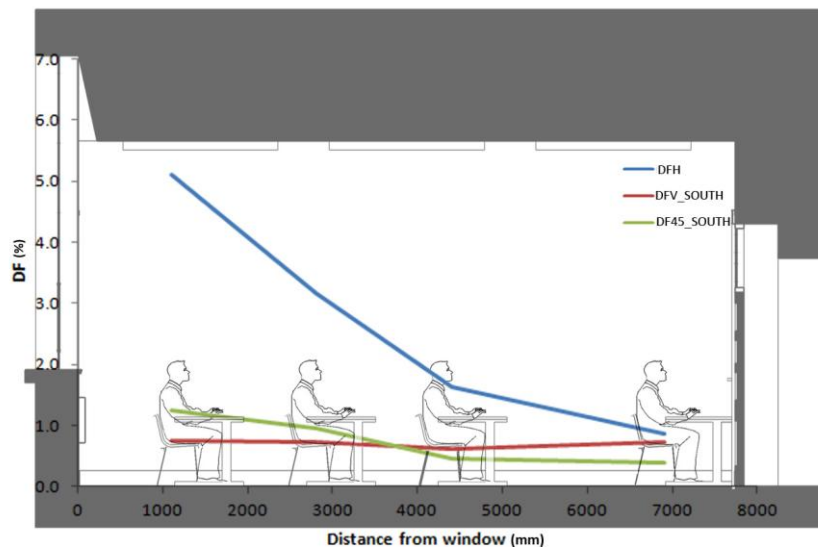


Figure E.2: Section through room showing DFV and DF45 values facing 180° from window wall in comparison to DFH values

Assuming that the people within this example room are facing the teaching wall (i.e. facing away from the window), then a comparison with the DF_V and DF_H values shows that DF_{45} exhibits behaviour much closer to DF_V than DF_H . The data also shows that initially the daylight factor measurement at 45° (DF_{45}) is higher than the DF_V value nearest the window. Figure E.2 shows this is still a significant reduction from the Horizontal DF values but it appears that the 45° gaze position facing the desk is benefitting from a greater amount of light reaching the desk and being reflected back to the eye.

This apparently obvious relationship is emphasised by the fact that the further into the room the person is positioned the more the light falling on the horizontal plane decreases and in turn the DF_{45} decreases. At approximately 4m into the room from the window wall the DF_{45} value drops below the DF_V value and by the farthest point from the window the DF_{45} value is 50% lower than the DF_V . At this furthest point within the example room the DF_{45} value is the lowest of the three angles of measurement; horizontal, vertical and 45°. The 45° measurement helps clarify the point at which reflectance from the walls becomes a more important contributor to daylight at a point than the direct light from the windows.

Table E.1: DFV_SOUTH and DF45_SOUTH values as a percentage of DF_H values based on position within example room

		DF _{V_SOUTH}	DF _{45_SOUTH}
Position within example room	Distance from window	% of DF _H value	% of DF _H value
A	1100	15	24
B	2800	23	30
C	4400	38	28
D	6900	85	45

Table E.1 shows the DF_V and DF₄₅ values as a percentage of DF_H available at each position in the room when facing South towards the teaching wall. The available light at eye level of a person sitting in this position is consistently low across the depth of the room, and is only similar to the horizontal value at the back of the room. This further emphasises that it is not very accurate to estimate the light reaching a person's eye level based solely on the horizontal illuminance measurement. A person who is sitting in positions A to C (most likely student locations), either looking at the teaching wall or at the desk surface would expect to receive less than 38% of the light falling on the horizontal surface on average.

If the orientation facing away from the window wall is considered the worst case scenario, it is important to compare this with what might be considered the best case scenario, i.e. directly facing the window, or north as represented in this example room. The DF₄₅ values for this orientation are now more similar to the DF_H values, rather than the Vertical DF, with the exception of position A nearest the window, which is unrepresentative of a typical single aspect room for the reasons noted earlier in the Chapter. This is shown in Figure E.3.

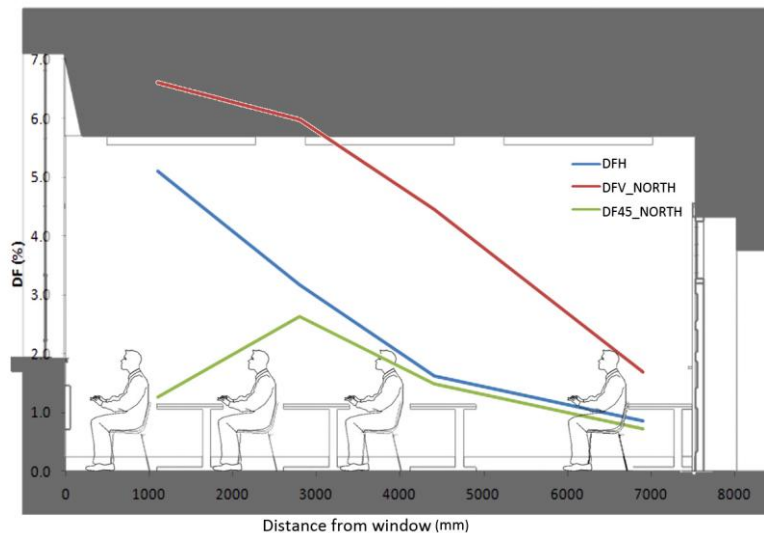


Figure E.3: Section through room showing DF_V and DF_{45} values facing the south wall/window wall in comparison to DF_H values

By excluding the value for position A there is an average reduction in DF_{45} value of approximately 15% from the Horizontal DF measurement. In positions B and C this orientation facing the window and angle of gaze could be seen to simulate a group working scenario in which the people sat in these positions have turned around to look at a piece of work on the table behind them. Even with this downward facing angle of gaze the DF_{45} value remains above 2.0% until a depth of approximately 3.5m from the window wall and falls below 1.0% at a distance ≥ 6 m from the window as shown in Figure E.3. These DF_{45} values remain higher across the depth of the room in comparison to those described above when the orientation is towards the south wall.

Table E.2: DFV_NORTH and $DF45_NORTH$ values as a percentage of DF_H values based on position within example room

Position within example room	Distance from window	DFV_NORTH	DF_{45_NORTH}
		% of DF_H value	% of DF_H value
A	1100	130	25
B	2800	190	83
C	4400	270	91
D	6900	200	84

In this orientation directly facing the window there is a significant variation between the DF_V and the DF_{45} values represented by a 65-80% reduction based on position within the room. This is slightly skewed by the results from position A as discussed above but by taking these

results out there is still a potential average reduction of 60% from the DF_V values to the potential DF_{45} values.

As might be expected from the previous section, there is a significant difference between the DF_{45} values facing north and south within the example room when position A is ignored. The variation in DF value between the two sets of results shown in Table E.3 is greatest at position B, 2800mm from the window wall, and reduces further into the room until the illuminance levels decrease significantly at 6000mm from the window and beyond.

Table E.3: Comparison of DF_{45} values facing north (towards window wall) and south (away from window wall)

Distance from window (mm)	DF_{45_SOUTH}	DF_{45_NORTH}	Difference between DF_{45} values	% variation in DF_{45} values
1100	1.2	1.3	0.1	8
2800	1.0	2.6	1.6	62
4400	0.5	1.5	1.0	67
6900	0.4	0.7	0.3	43

The DF_{45} values for both orientations facing 90° from the window wall are similar across the depth of the room with the exception of position A nearest the window as shown in Figure E.4. At position A the DF_{45} value facing the west wall is approximately 35% less than the value facing the east wall. This difference between the East and West orientation is mirrored in the DF_V values where there is similarity in form between the sets of data again with the exception of position A nearest the window. There is a reduction of approximately 45% between the DF_V value facing the east wall and the value facing the west wall.

As can be seen in Figure E.4 there is a greater difference between the DF_V and DF_{45} values when facing the West wall within the room than when facing the East wall. When considering a downward angle of gaze represented by the DF_{45} values there seems to be less impact from the proximity to a vertical surface with the two sets of data being similar across the room with the exception of the point closest to the window. This emphasises the observation made above that the majority of light received at this 45° downward facing angle is reflected from the horizontal surface.

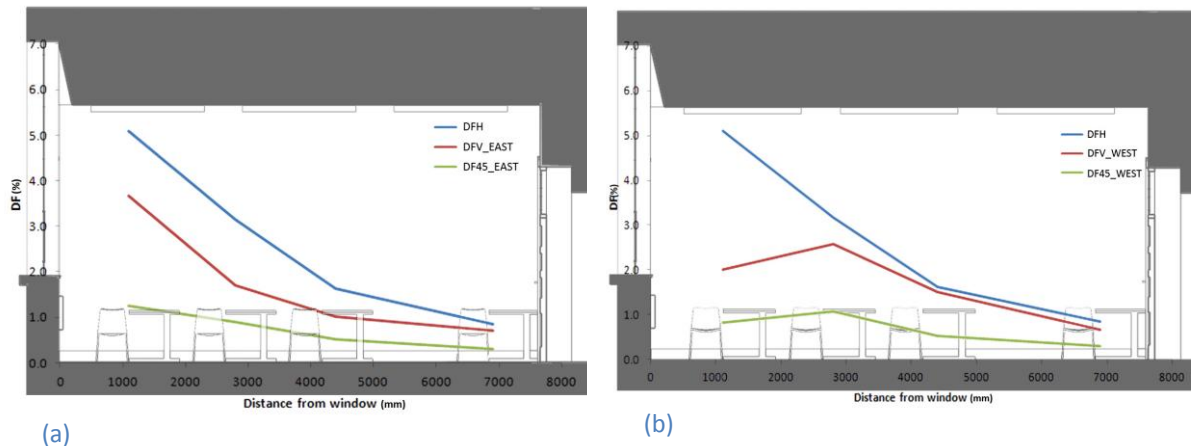


Figure E.4: Section through room showing DF_V and DF_{45} values for two orientations (a) towards East wall (b) towards West wall in comparison to DF_H values

This analysis of the DF_{45} values across the example room shows that the direction a person is facing or their orientation within the room does have an impact on the amount of light that is received at eye level. Table E.4 expresses the measured DF_{45} values at each seating position within the room based on the different orientation of view. This highlights that the variability of daylight distribution based on the different orientations, as the variation between the lowest and highest DF_{45} values at each seating position within the room fluctuates from 38-67%. Overall the orientation or direction someone is facing within the room could alter the amount of light that reaches their eye level by 57% on average based on a downward angle of gaze.

Table E.4: DF_{45} values for all four seating positions based on orientation

Distance from window (mm)	DF_{45_NORTH}	DF_{45_SOUTH}	DF_{45_EAST}	DF_{45_WEST}	Max. variation in DF_{45} value	Max. variation as % of greatest value
1100	1.3	1.2	1.2	0.8	0.5	38
2800	2.6	1.0	0.9	1.1	1.7	65
4400	1.5	0.5	0.5	0.5	1.0	67
6900	0.7	0.4	0.3	0.3	0.4	57

Table E.5 shows the DF_{45} values for the four orientations against the position within the room, therefore the distance from the window. This shows that there is a greater impact DF_{45} values across the room as a result of the distance from the window wall. With the exception of the results from DF_{45_SOUTH} which represents a person facing away from the window, this suggests that there could be up to 75% variation in DF_{45} value across the depth of the room.

Table E.5: DF₄₅ values for all four orientations based on seating position/distance from the window wall

Orientation at each position	A (1100mm)	B (2800mm)	C (4400mm)	D (6900mm)	Max variation btwn DF ₄₅ values	Max. variation as % of greatest value
DF ₄₅ _NORTH	1.3	2.6	1.5	0.7	1.9	73
DF ₄₅ _SOUTH	1.2	1.0	0.5	0.4	0.6	50
DF ₄₅ _EAST	1.2	0.9	0.5	0.3	0.9	75
DF ₄₅ _WEST	0.8	1.1	0.5	0.3	0.8	73

This emphasises that the when a person is looking down towards the desk the distance they are sat from the window will have the greatest effect on the amount of light received at their eyes. It is evident that only when directly facing the window might this be counteracted by an increased amount of light being reflected from the horizontal desk surface. Even taking this into consideration the DF₄₅ values across this example room are low. Based on each position within the room which corresponds to a distance from the window wall the average DF₄₅ value did not get above 1.4.

Table E.6: DF₄₅ values for all seating positions based on orientation compared to DF₄₅ average and DF_v average

Distance from window (mm)	DF ₄₅ _NORTH	DF ₄₅ _SOUTH	DF ₄₅ _EAST	DF ₄₅ _WEST	Avg. DF ₄₅ value	Avg. DF _v value
A 1100	1.3	1.2	1.2	0.8	1.1	3.3
B 2800	2.6	1.0	0.9	1.1	1.4	2.8
C 4400	1.5	0.5	0.5	0.5	0.8	1.9
D 6900	0.7	0.4	0.3	0.3	0.4	1.0

The DF₄₅ values range from 16-85% less than the Horizontal DF values. This represents a considerable variation in light distribution between what is achieved at the horizontal plane to what might reach the eyes of a person sat looking toward the desk at a visual task. For example if a point on a horizontal working plane achieves 500lux the amount of light received at the eye of an individual person could range from 420lux down to 75lux depending on their position within the room.

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Appendix F

**Further analysis of the adjustment of surface colour on light distribution
within the Case Study room**

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This appendix builds on the analysis included within Chapter 8 of the effect of surface colour on the light distribution within the Case Study room. This was analysed as part of the calibration of the computer generated model created in *3ds max design*.

The variations in the illuminance levels simulated by the computer model depending on changes to the colour of surfaces within the room suggested that this design parameter could have a significant impact on the distribution of light throughout an internal space. This would in turn have an impact on the amount that is received at eye level by people within the room.

The implication of changing this design parameter was examined a little further to establish whether it was possible to achieve a closer fit between the physical and the virtual measurements. The surface colours that were used for the *Measured Colour* dataset shown in Table F.1 were adjusted based on realistic assumptions about the physical room, for example the colour of the ceiling colour was darkened to replicate the degeneration of the ceiling tiles through collection of dust and dirt. The wall colour and the floor colours were kept the same to ascertain the impact of the colour of the other surfaces within the room. The adjusted set of surface colour specifications is shown in Table F.1 alongside those used with the *Measured Colour* simulation.

Table F.1: Measured and Adjusted RGB colour values for surfaces within computer model

Room surface	Finish	Colour specification: <i>Measured Colour</i>			Colour specification: <i>Adjusted Colour</i>		
		R	G	B	R	G	B
Wall	Light Green gloss paint	0.768	0.809	0.741	Not adjusted		
Floor	Dark Maroon/Brown carpet	0.502	0.443	0.502	Not adjusted		
Ceiling	White plasterboard ceiling tiles	0.612	0.58	0.608	0.21	0.208	0.192
Desk surface	Medium wood veneer	0.898	0.808	0.725	0.788	0.627	0.490

Figure F.1 below shows the DF values recorded within the example room based on these *Adjusted* surface colours. There are small but measurable differences between this set of data and those based on the *Measured Colour* values. In terms of the horizontal DF values there is a difference of approximately 3-10% across the depth of the room compared with the *Measured Colour* data, this is represented by a reduction at the position nearest the window and a small increase at the furthest position from the window. Even with these adjusted surface colours there is still a 10-30% difference between the daylight distribution reported by the computer model and that measured within the room itself.

In terms of the DF_V values for the vertical orientation South (180° away from the window) there is a similarity between the two sets of values from the middle of the room at position C to the furthest point from the window. At position A, approximately 1m from the window, the *Adjusted Colour* model reports a reduction in DF_V value of approximately 20% from the *Measured Colour* model. This is potential a result of the change in surface colour of the desk as well as the ceiling as at this point within the room it is likely that the light sensor is picking up mostly reflected light from the surrounding surfaces. It is evident that adjusting the colour of these two surfaces has a negligible effect on the light received at position at the back of the room.

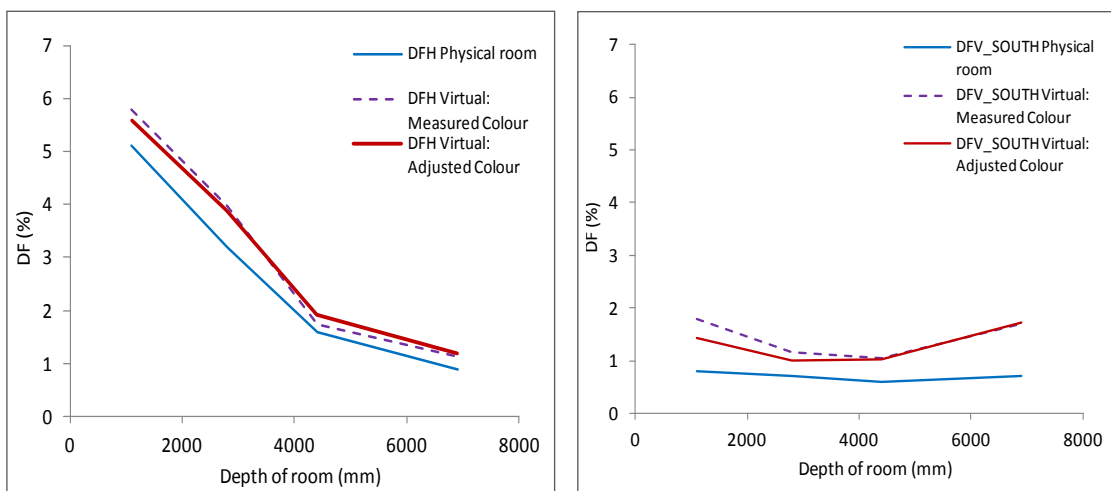


Figure F.1: Comparison of (a) horizontal and (b) vertical DF values taken in the physical room against those taken in the virtual model based on adjusted surface colour specification as well as reflectance values

Even with these adjustments to the surface colours there is still a noticeable difference between the DF values reported by the computer model and those recorded within the physical space. For the horizontal DF values there is a 10-30% difference with the computer model over-reporting across the depth of the room. In terms of the vertical DF values, for this orientation, facing away from the window, there is still a significant difference between the physical and the computer model readings, in particular at the furthest point from the window. This would not be expected and it is unclear from this investigation what the cause of this inaccuracy might be.

Based on this vertical orientation facing away from the window, the computer model is over-reporting the DF_V values by between 40-150% of those recorded in the physical model depending on position within the room. Comparing the other vertical orientations with the physical DF_V values measured represents a range of $\pm 2-25\%$ variation, when averaged this represents only 5% increase for the three orientations across the depth of the room. This

would suggest that more care is needed when assessing the daylight distribution on vertical surfaces throughout a space based on a computer simulation. In the process of calibrating the colour of the surfaces with more accurate information taken from the room it was possible to see the impact of changing the hue of a particular colour.

Taking all the vertical orientations into account the final computer model over-estimates the daylight distribution between 5-150% across the depth of the room. This over-estimation is seen most significantly with the South orientation which presents a variation to the physical measurements of 45-150% across the depth of the room. Excluding the readings for this South orientation the average variation is 5%. It is important to note although the over-estimation seems to be great at position D, these are small values therefore in reality the difference is small.